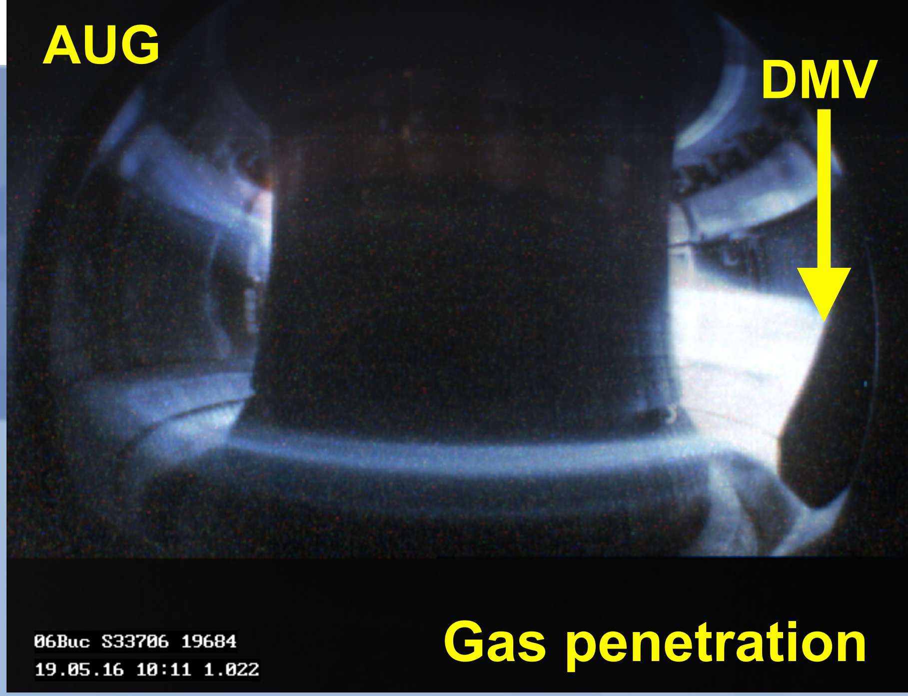

Runaway electron experiments on the European medium sized tokamaks ASDEX Upgrade and TCV

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RE scenario on AUG vs TCV

	AUG	TCV
R [m]	1.65	0.88
a [m]	0.5	0.25
B_t [T]	2/2.5	1.45
I_p [MA]	0.8/1.0	0.2/0.15
n_{e0} (10^19 m^-3)	2-3	0.3-4
T_{e0} [keV]	5-10	O(1)
Wall	W	C
Heating	ECRH	Ohmic
Shape	Circ.	Circ ++
MGI	Ar + Ar/Ne	(Ar + Ar)/(Ne + Ne)
I_{RE} [kA]	< 420	< 200
t_{RE} [ms]	< 500	350+
I_{RE} at loss [kA]	~25	~100

AUG runaway experiments

➡ **Understand RE dynamics with impurity injection**

1. Effect of disruption mitigation gases on RE dynamics
2. Influence of high-Z injection into developed RE beams

➡ **RE vs high-Z interaction studies in support of ITER**

- **Baseline: 0.8 MA, 2.5 T, 2-3e19 m^{-3} circular IWL plasma with ~2.5 MW ECRH heating for 100 ms pre-quench T_0 ~ O(10) keV**
- Disruption triggered with 0.5-1 bar Argon at 1 s (~1.7x10^{21} particles)
  ➡ Good beam control to 25 kA, **machine is safe**
- **IP is in programmed ramp-down**
- Factor of 2-5x increase in n_e
- **Good Ar assimilation, RE decay "understood"**

A typical AUG RE beam

Valve geometry (sketch)

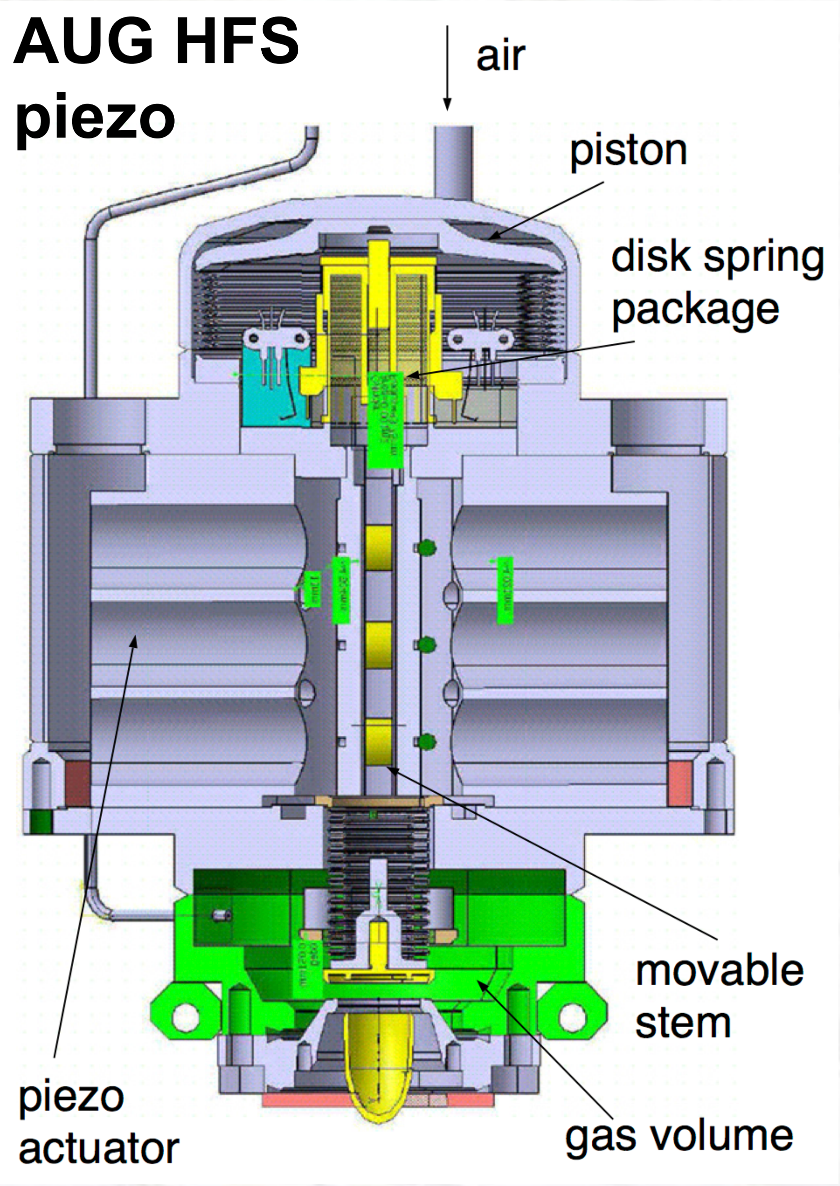
- AUG has a diverse DMV geometry

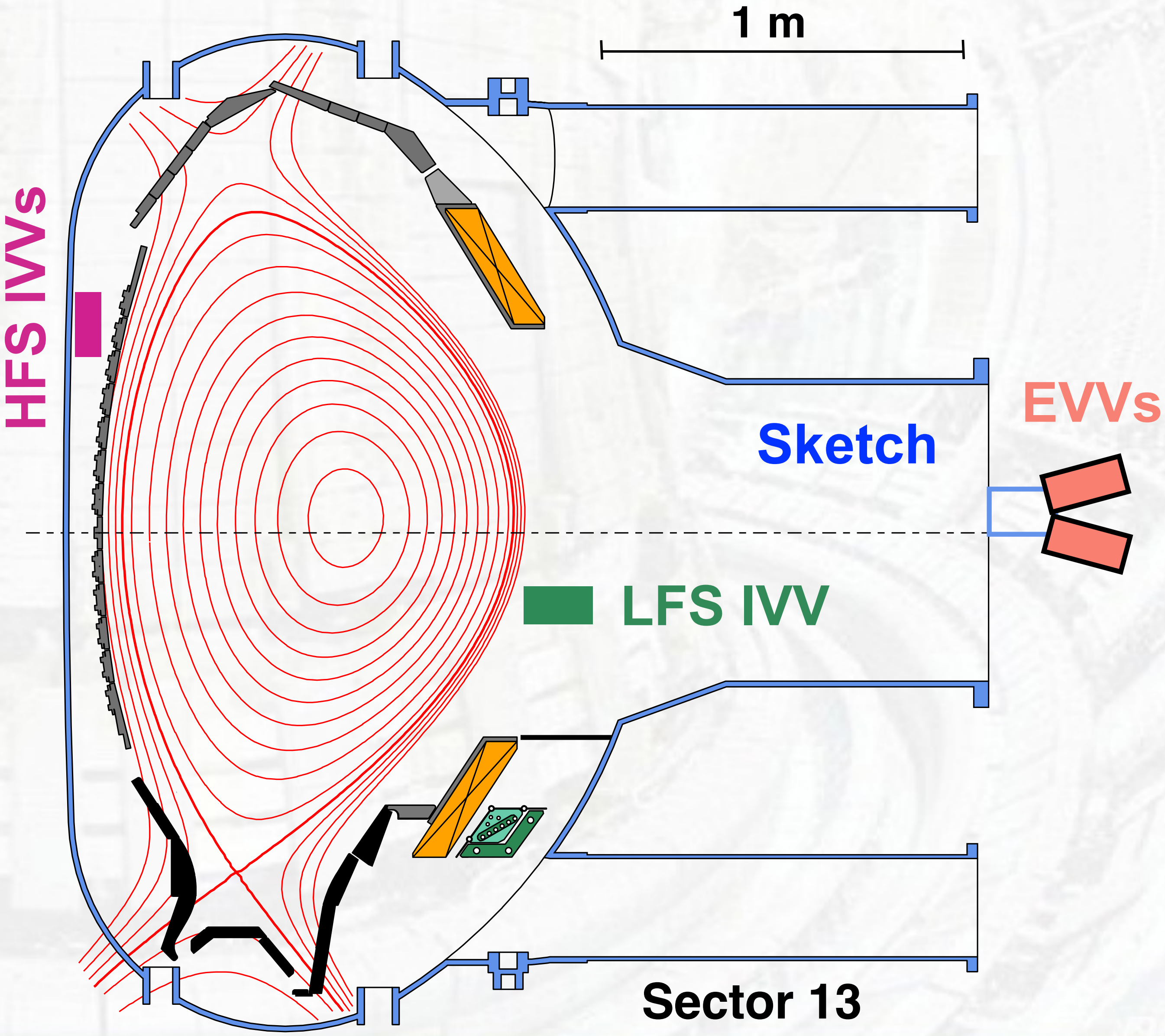
[Pautasso NF 47 900 (2007)]
[Pautasso NF 55 033015 (2015)]

➡ 2x Ex-vessel electromagnetic valves (50 ml ➡ "25" ml?)

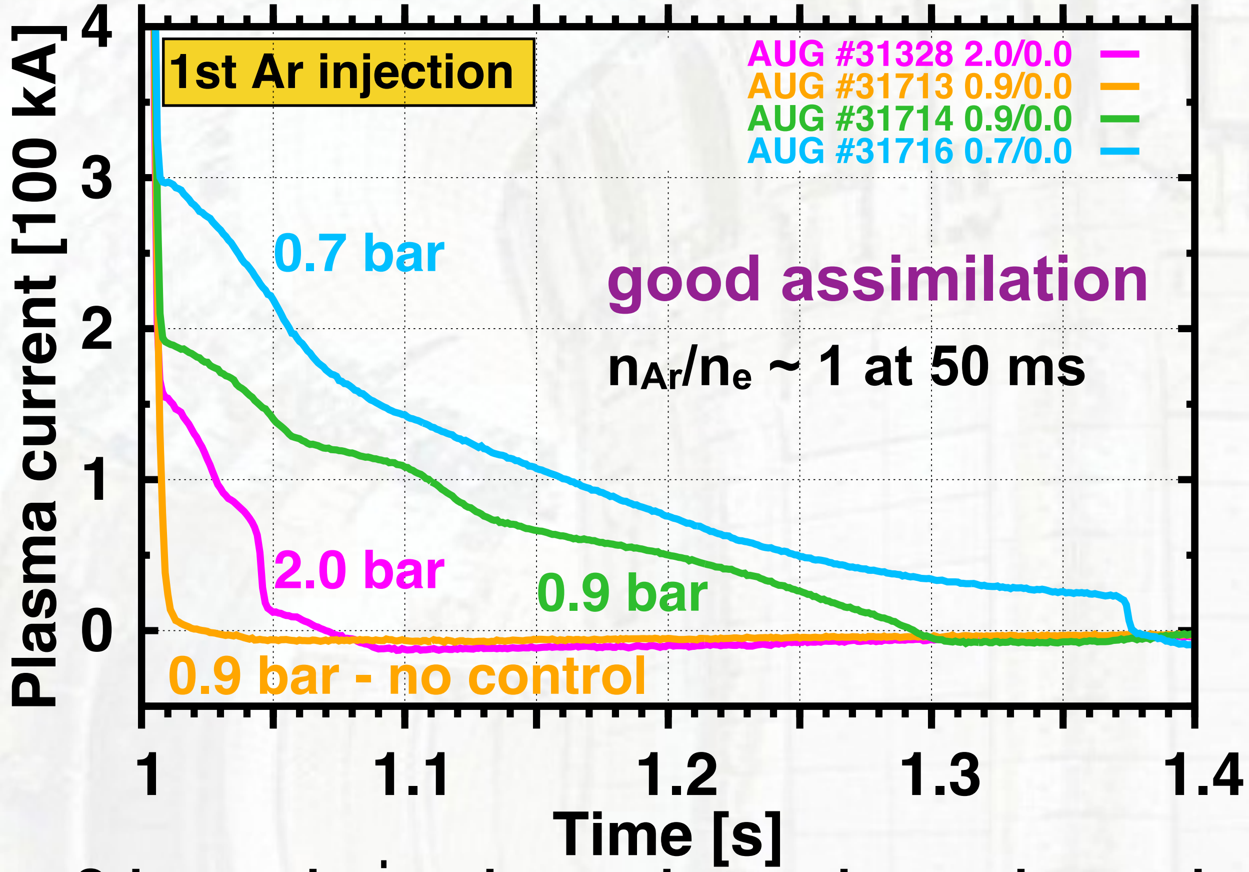
➡ **2x HFS and 1x LFS in-vessel piezo valve (100 ml)**

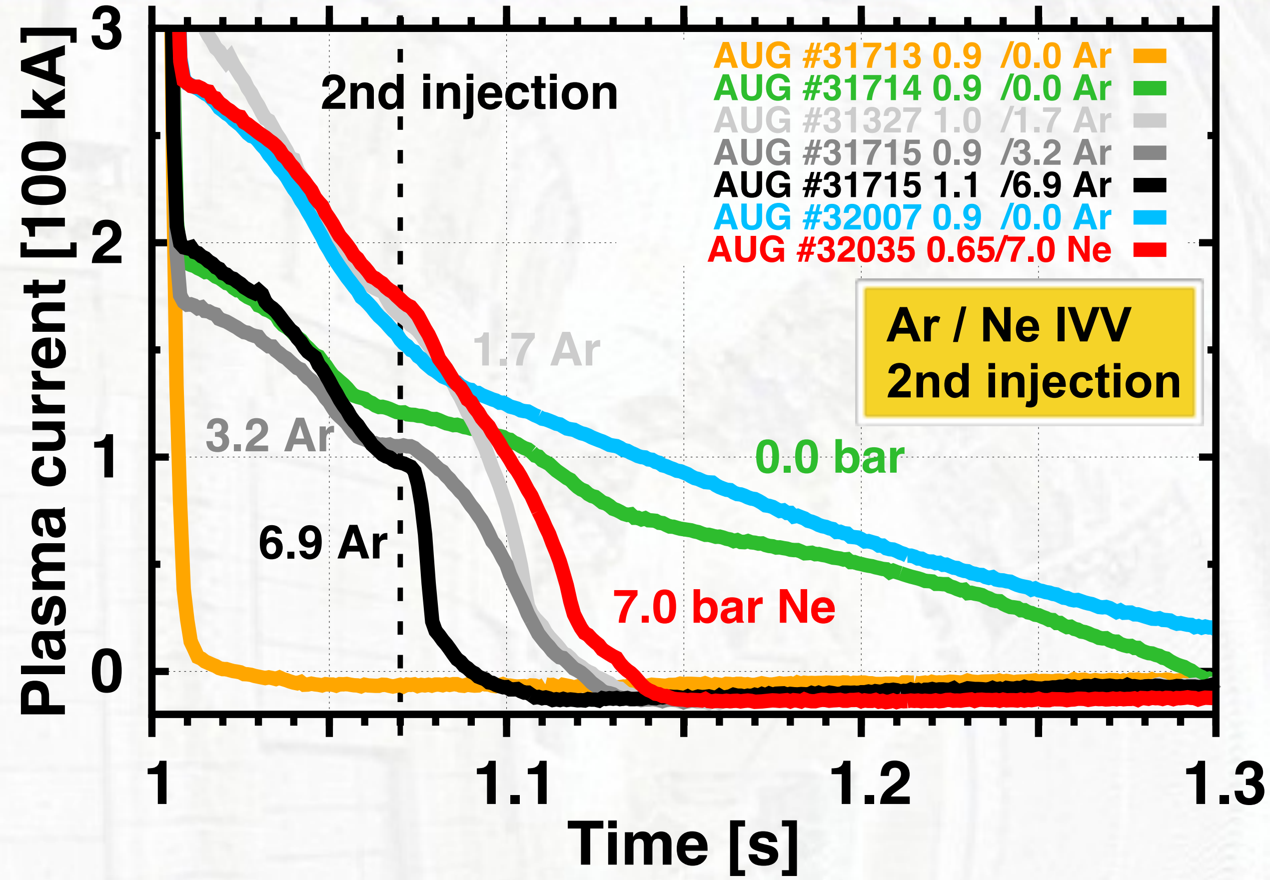
☠ HFS valves became disfunctional early in the RE campaign

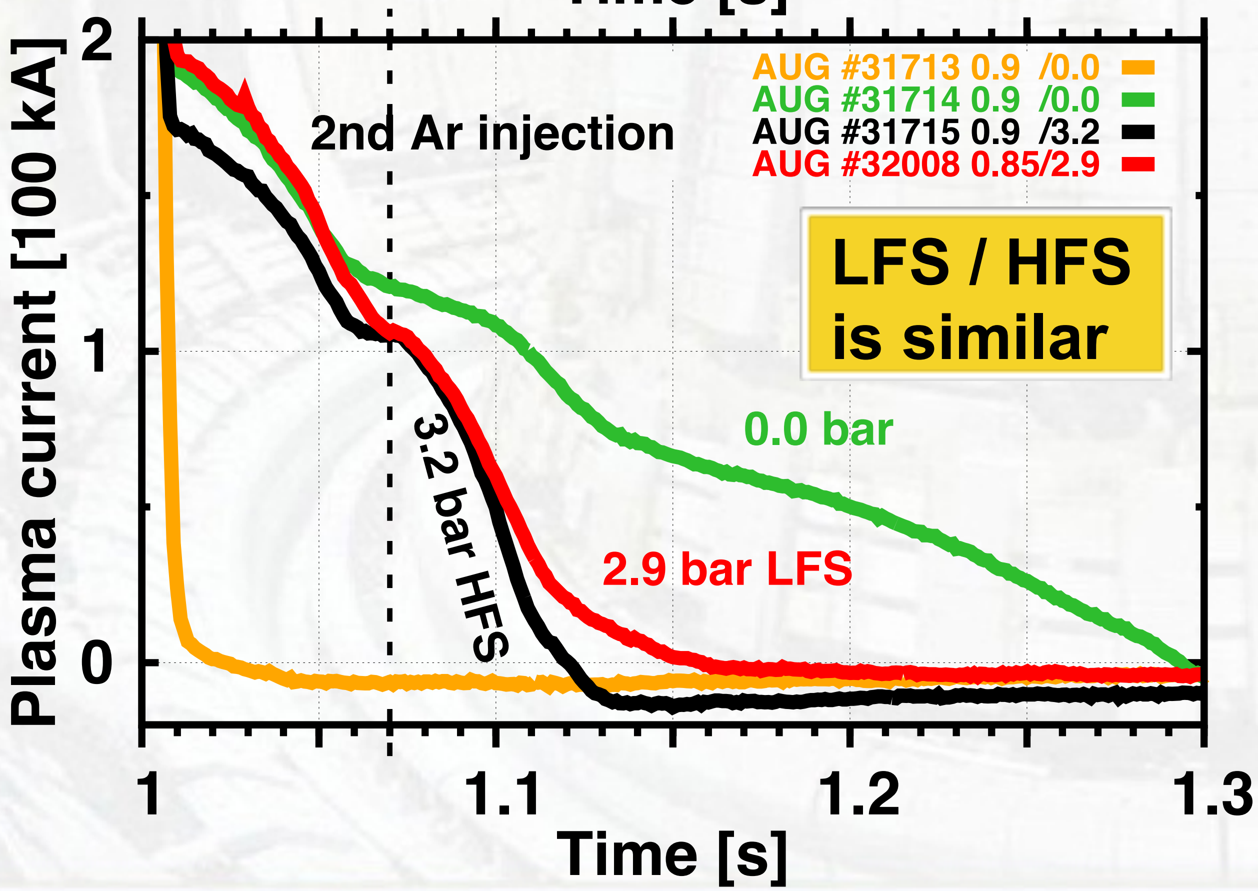


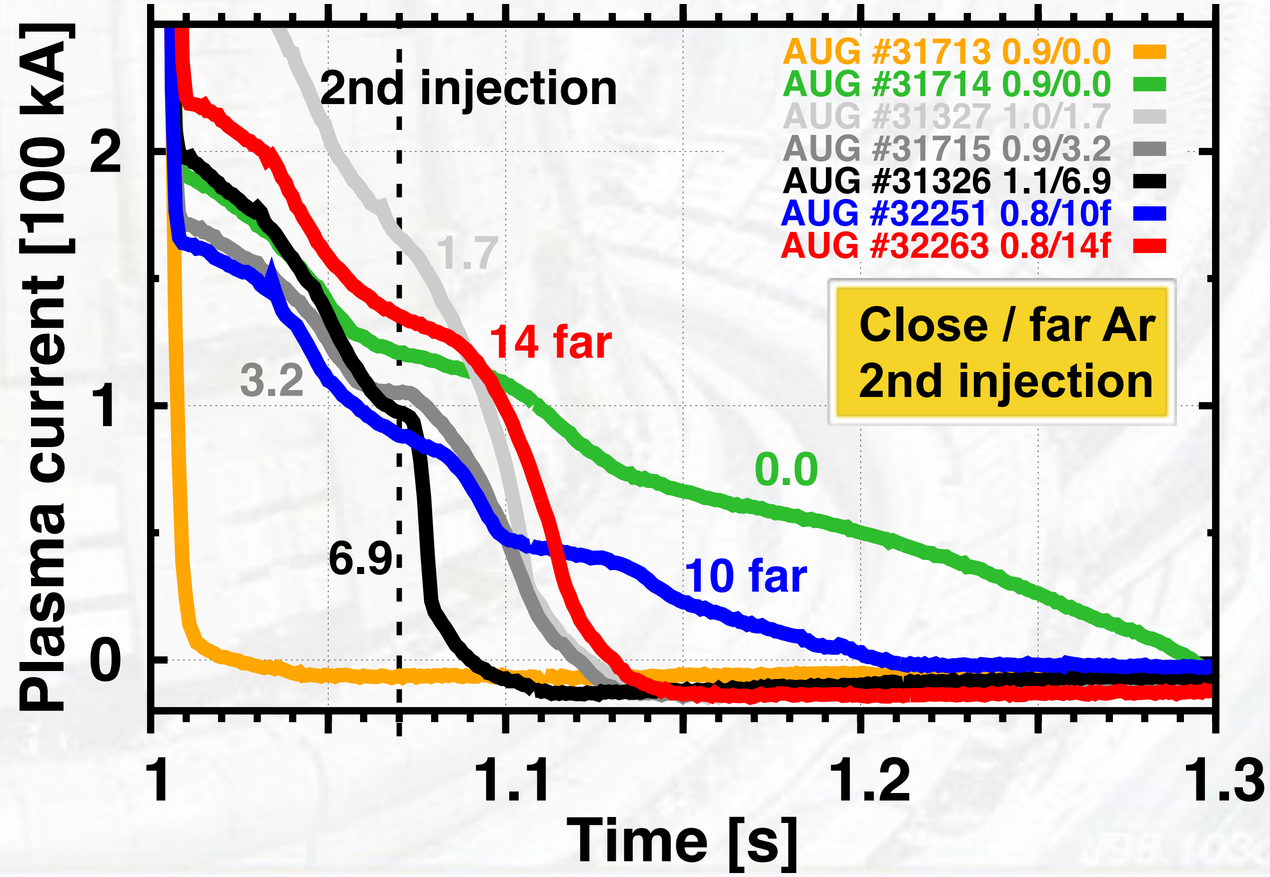


High-Z injection "scans"









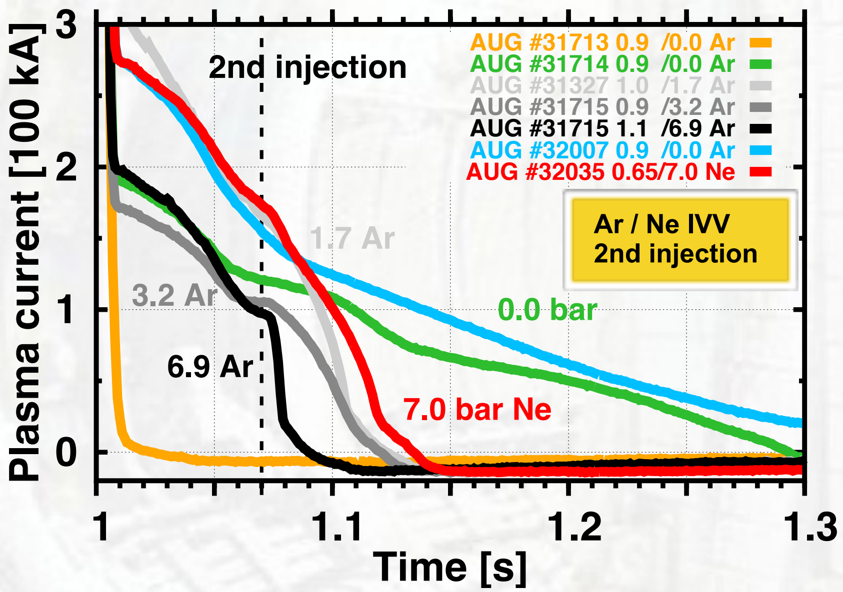
➡ **2nd injection with Ar seems to have a trend**

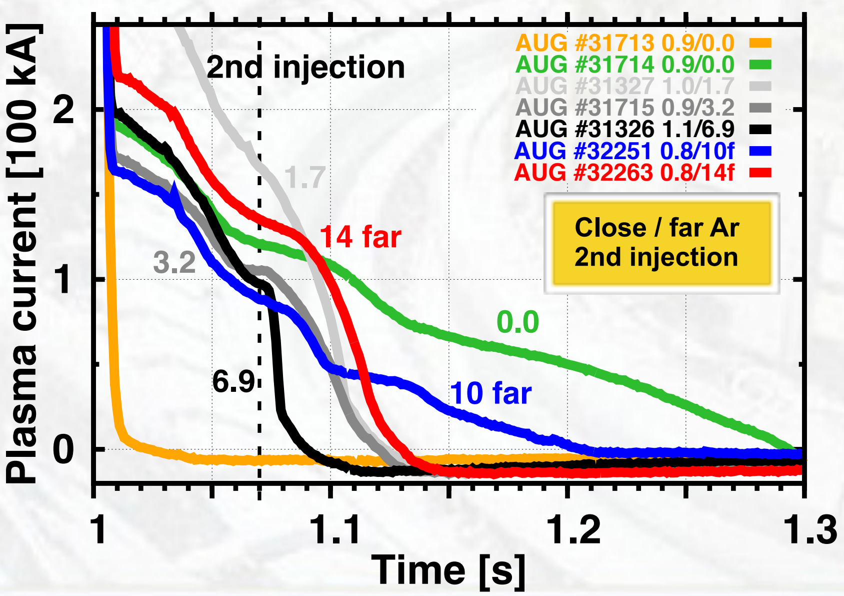
Other materials behave differently, but we need more points

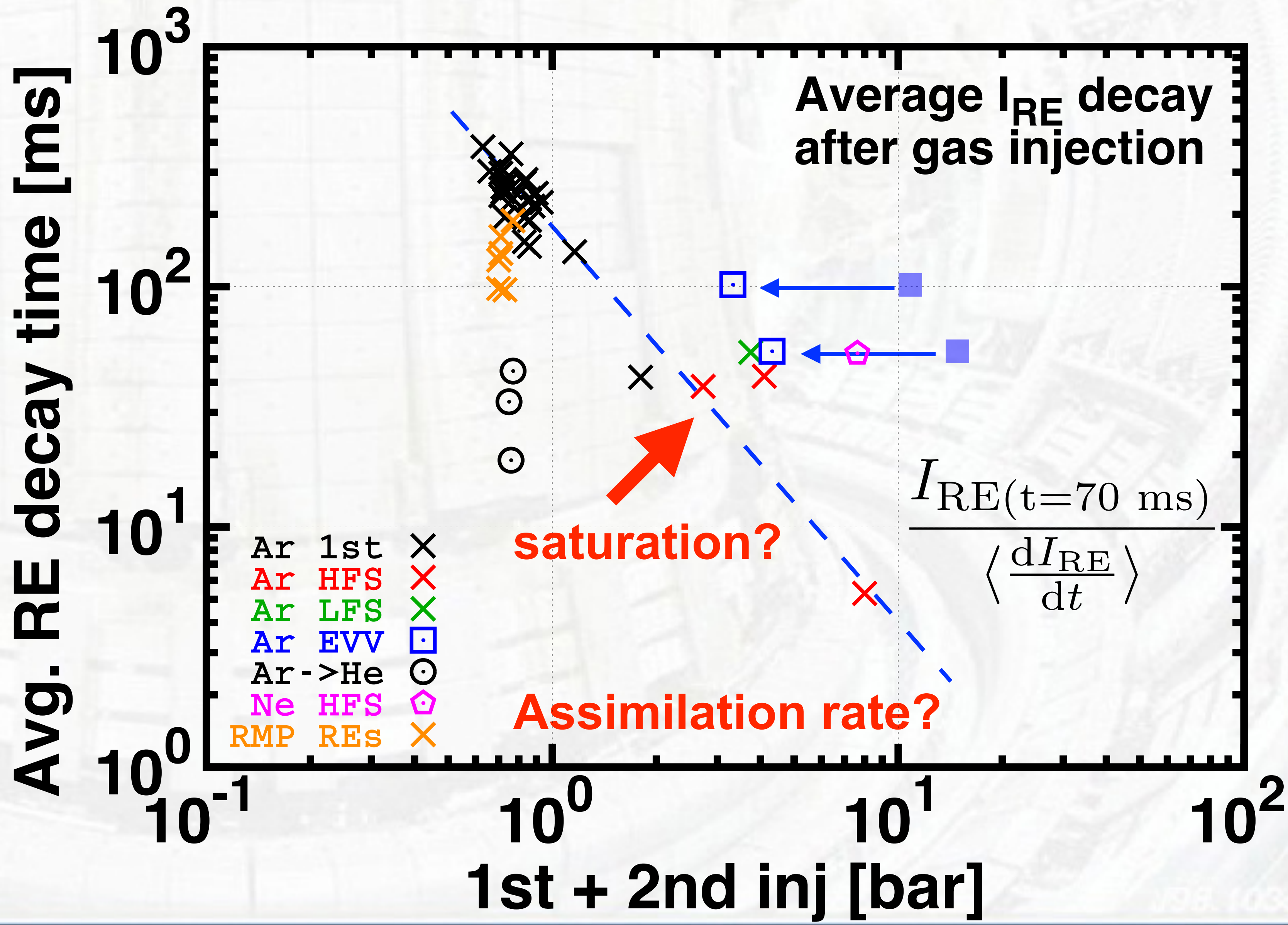
- [Aleynikov PRL 2015] suggests **dI/dt ~ n_{Ar}**

➡ **Trend is not clear in the data**

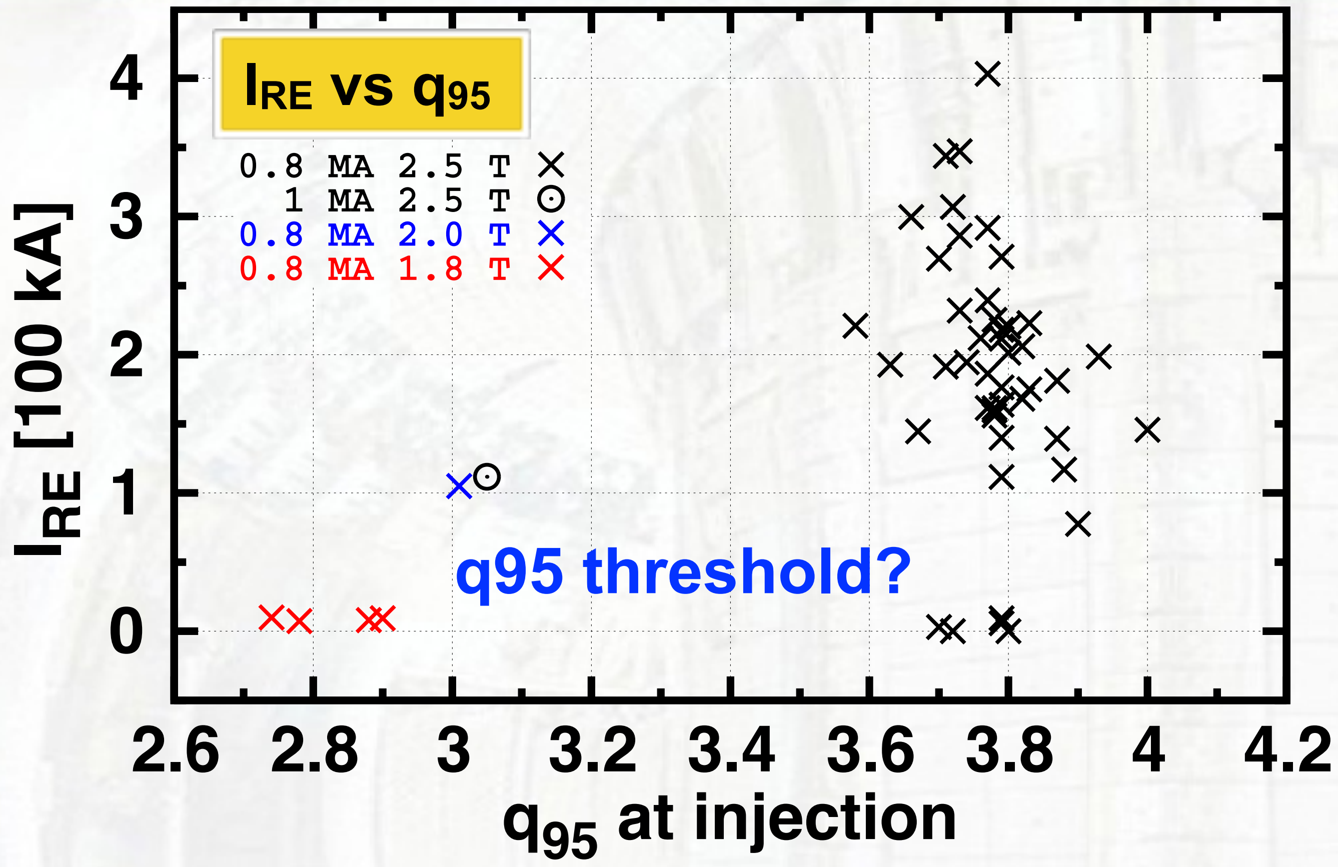
(we need more points & assimilation rate calculations)

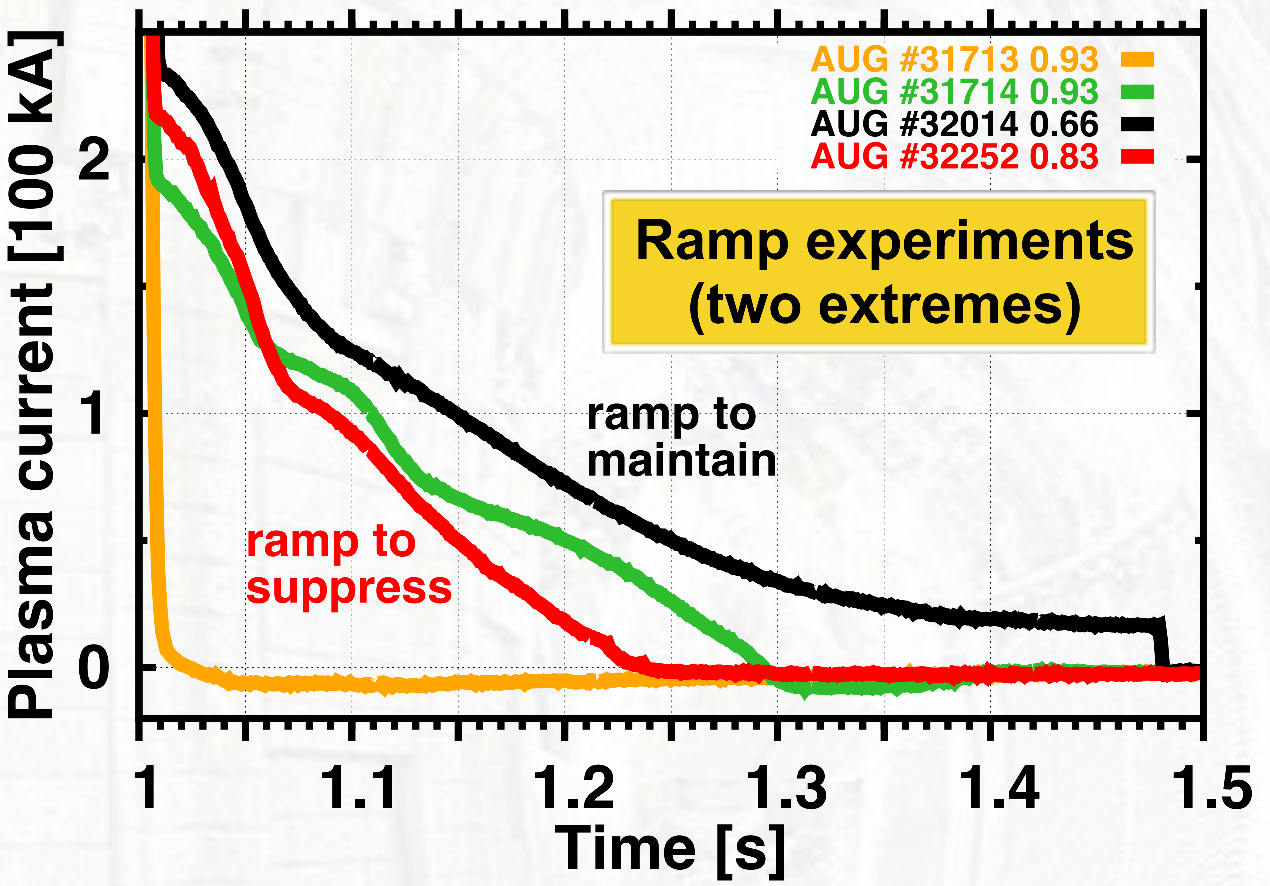


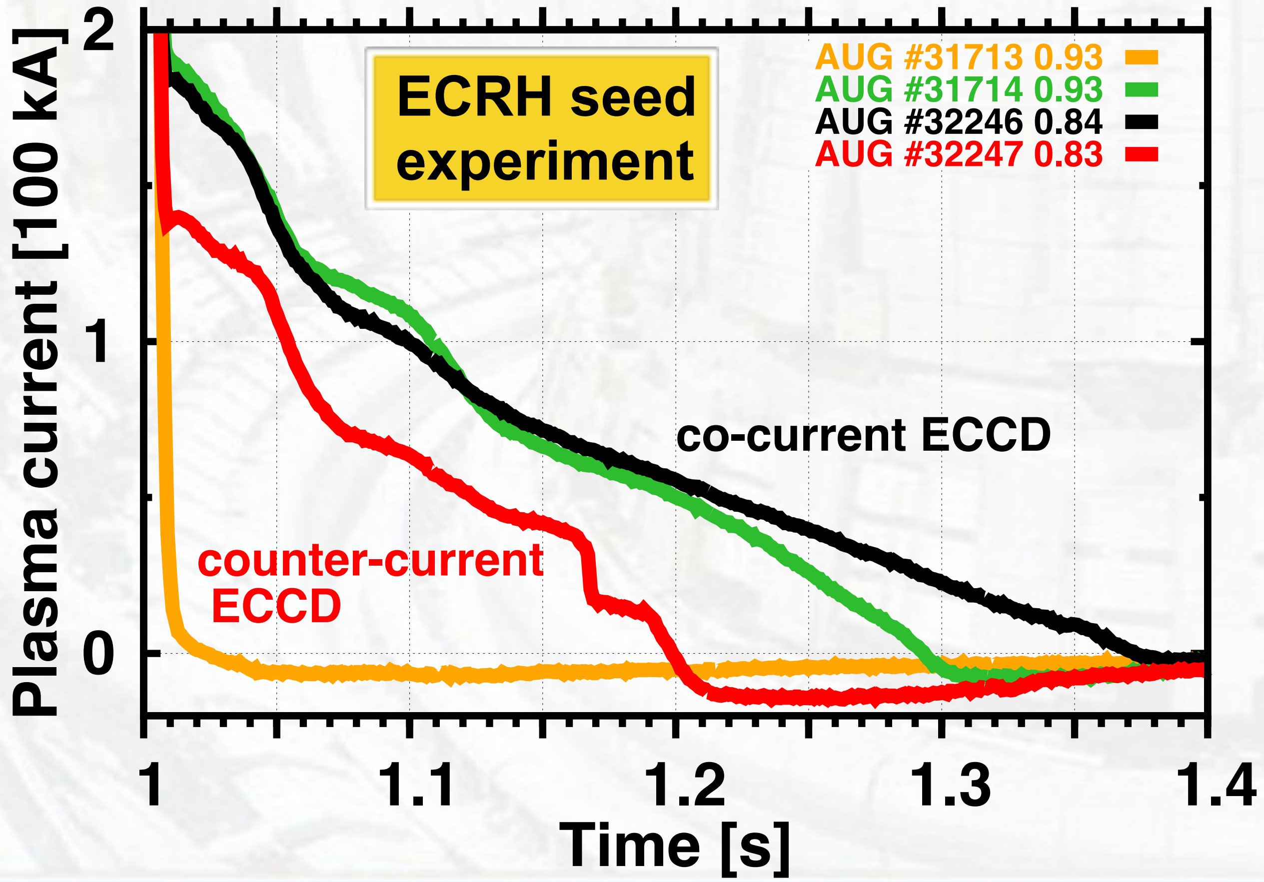


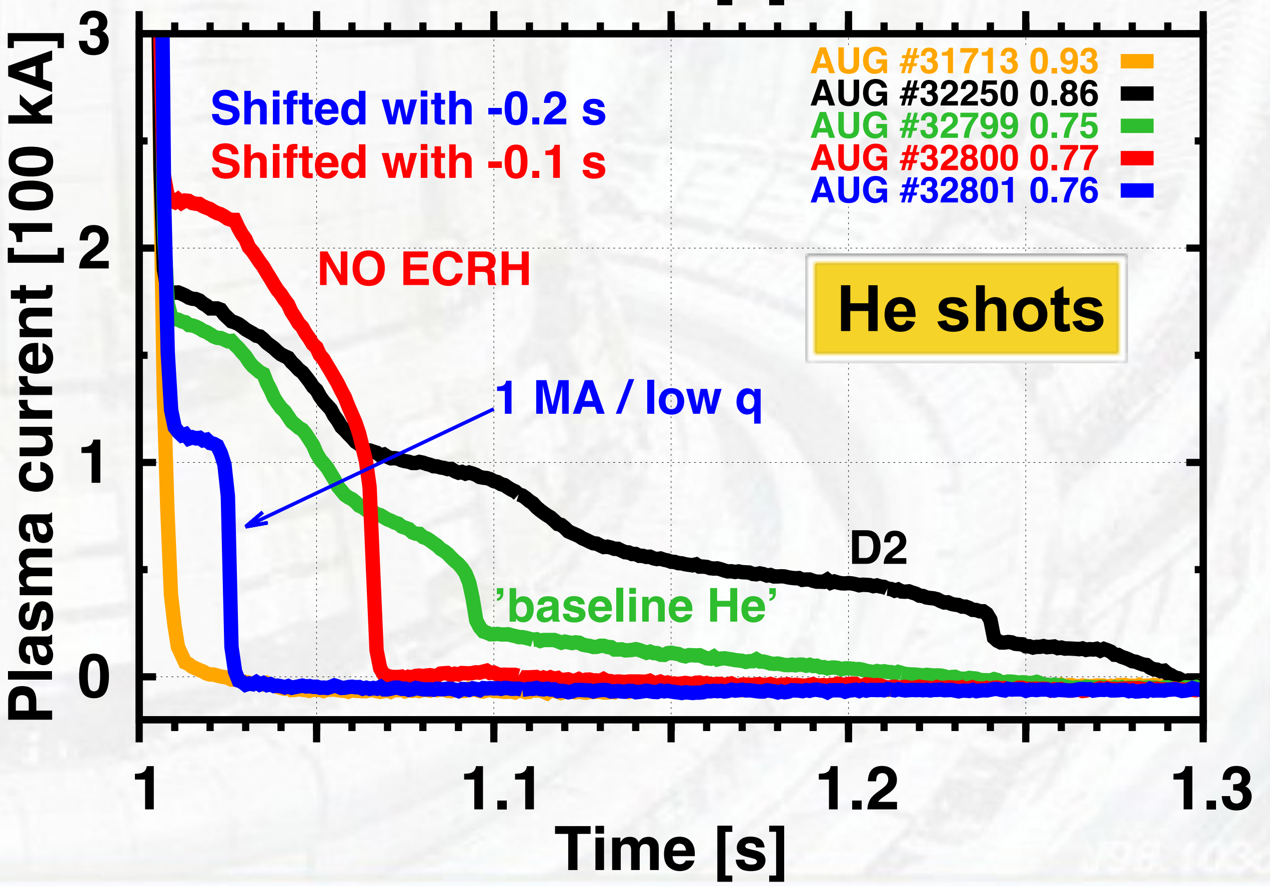


Study examples



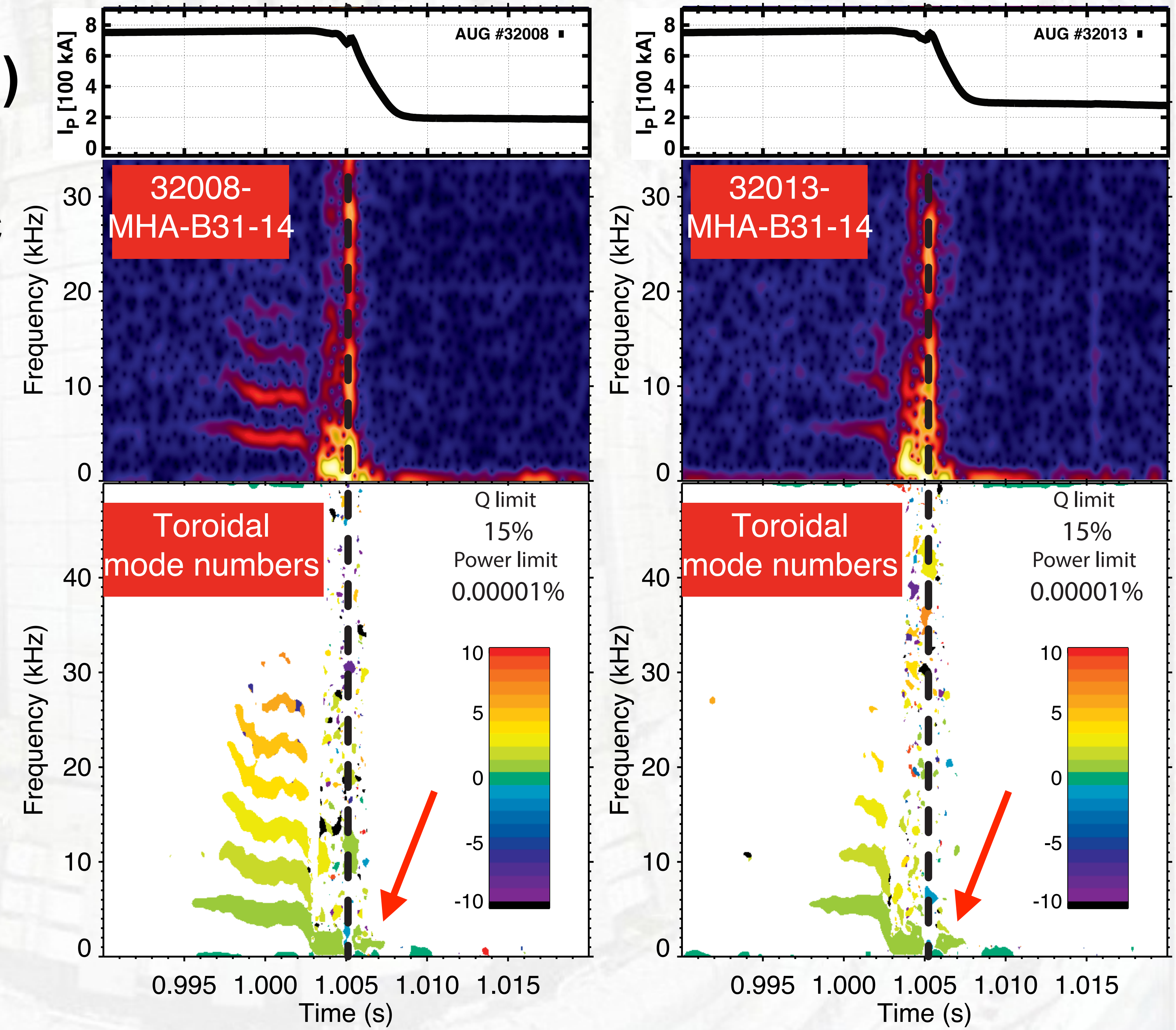






1/1 mode survives the TQ

- **1/1 mode develops (due to low density?) <u>before</u> injection**
- Becomes anharmonic and slows down
- **In most cases 1/1 survives the TQ**
  ➡ Core confined?
- So far no clear connection between mode parameters (*A*, *f*, etc) and REs
- Further analysis is ongoing

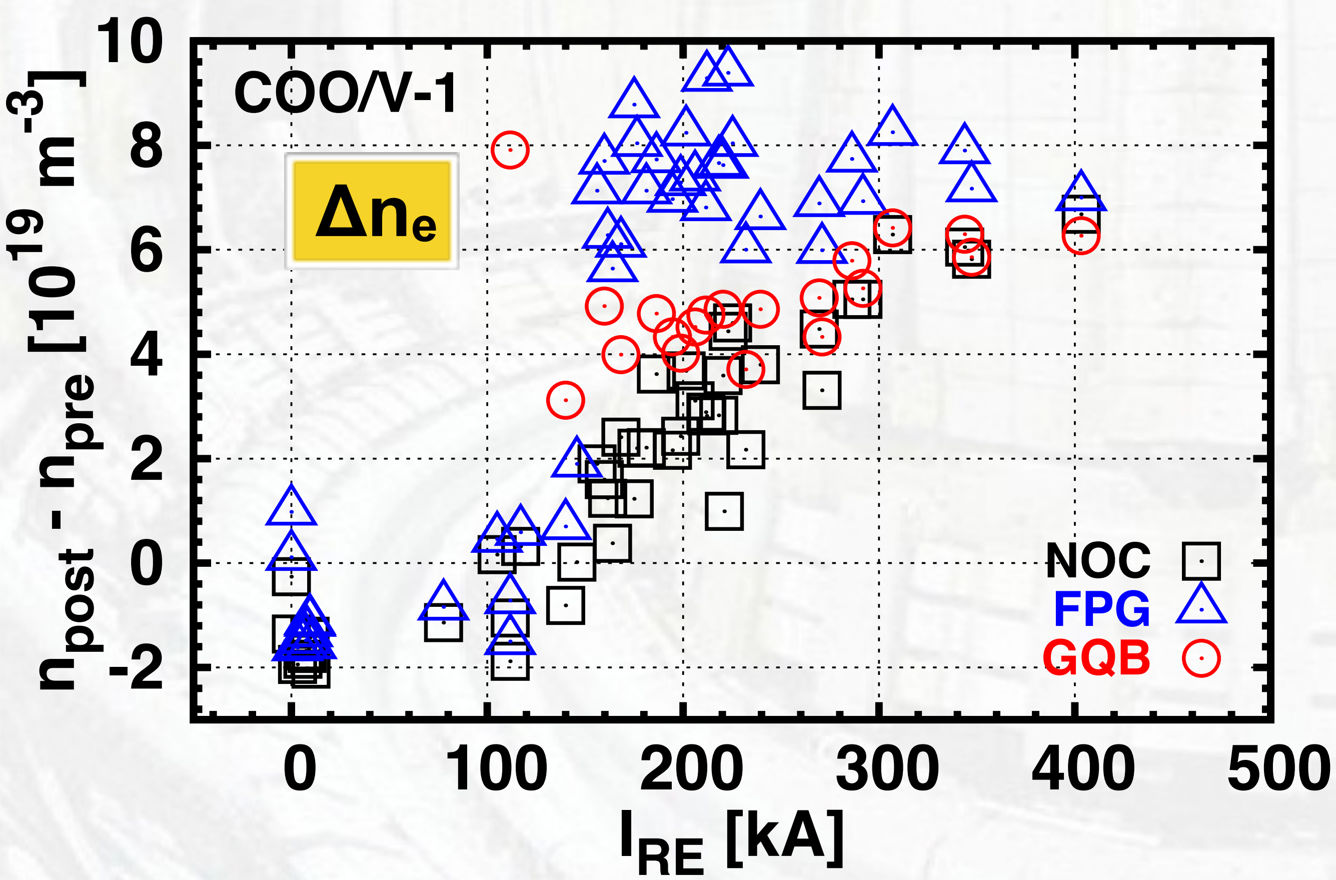


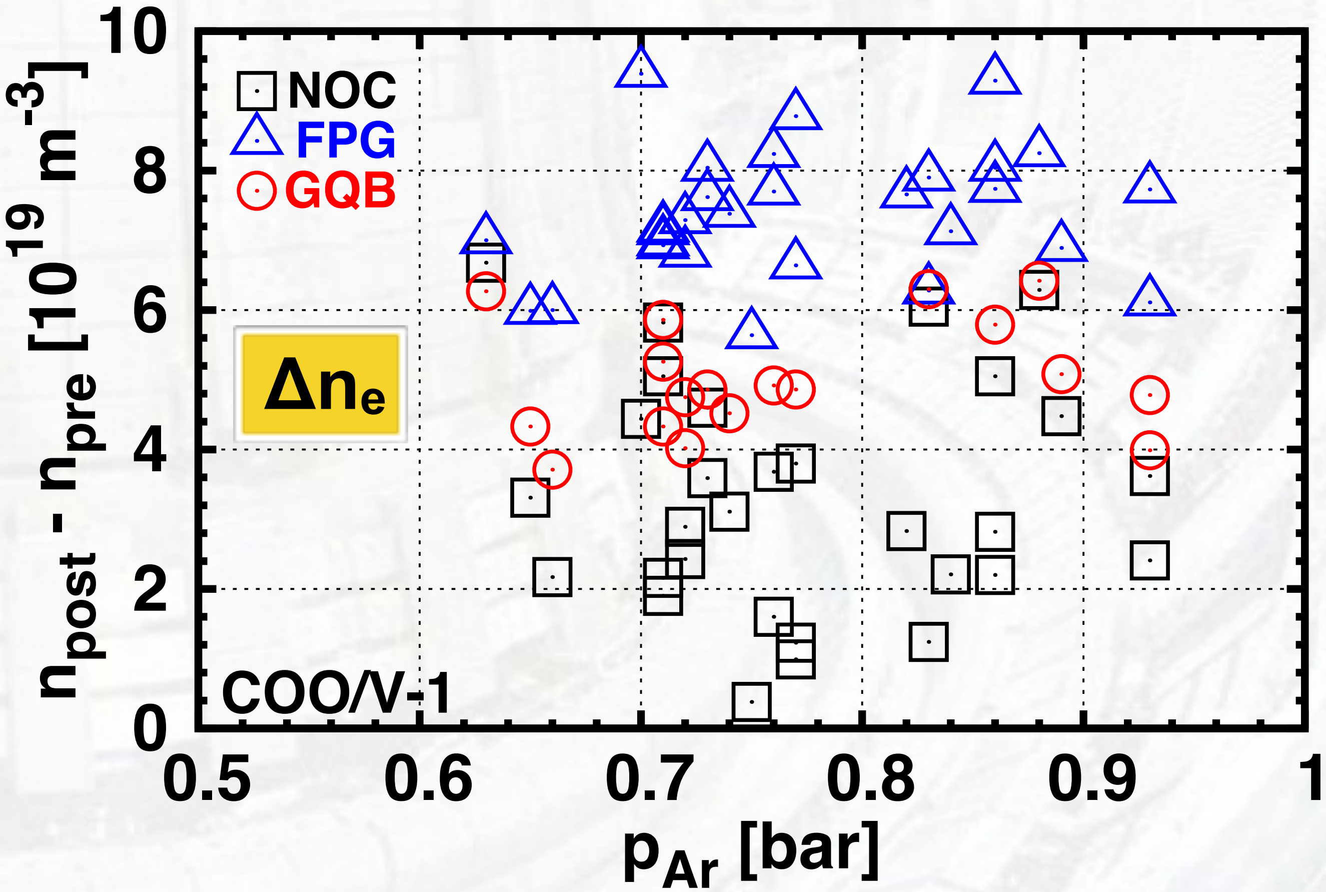
Complexities of data analysis

- Have to be careful with "out-of-the-box" data
- Some correlations are plausible (e.g. I_{RE} - Δr, Δa, HXR,neutrons)
- Some are missing: I_{RE} does not clearly correlate with characteristic parameters of temperature, density, loop voltage, heating, injection amount, fast particle / nuclear data... (etc)

  ➡ **Role of MHD mixing? Anything else?**

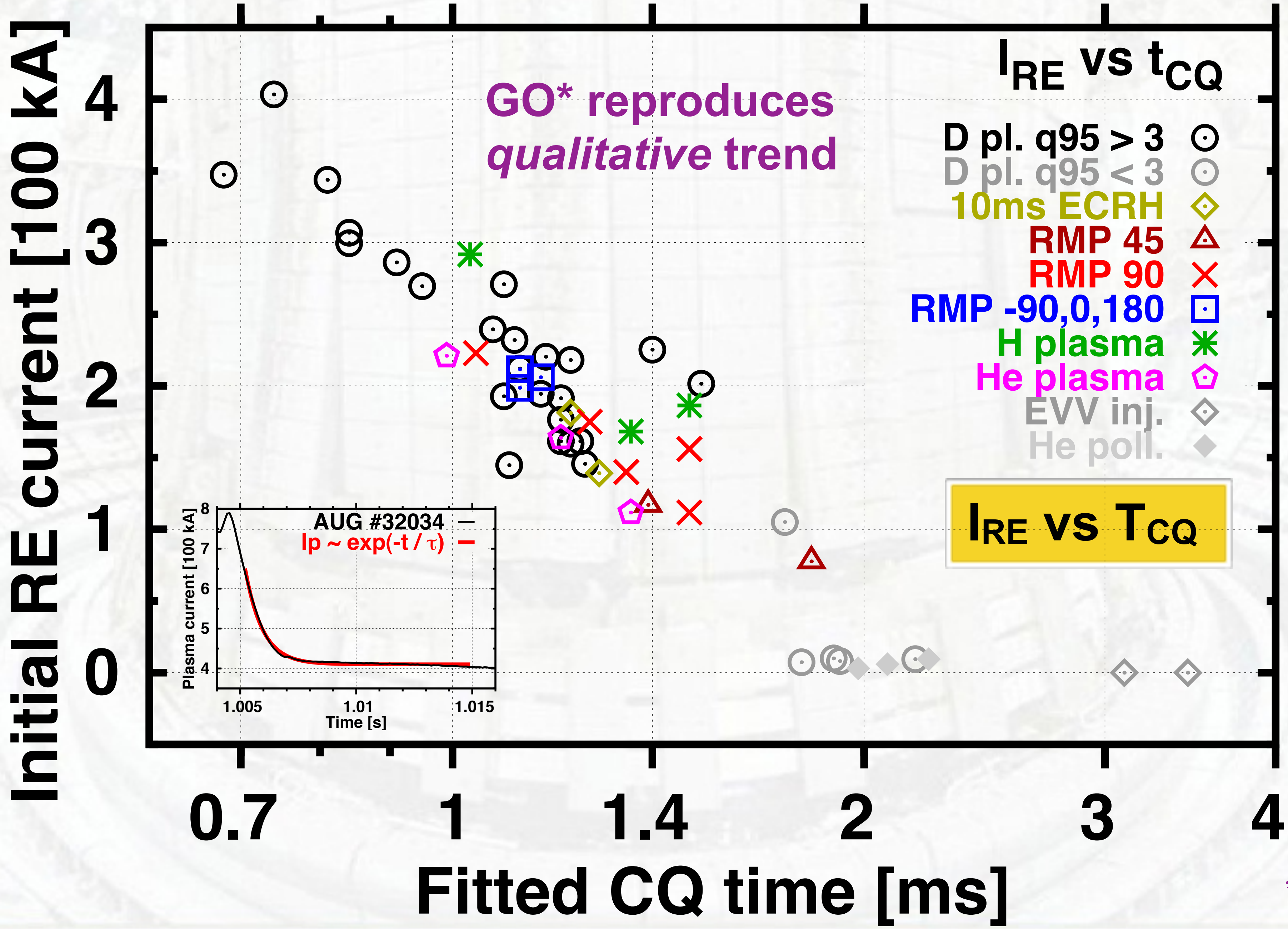
➡ But some interesting relations have been found





- Extracting "typical" V_{loop} or $E_{||}$ values is tricky, because
  ➡ $V_{loop}(t)$, and different measurements / calculations

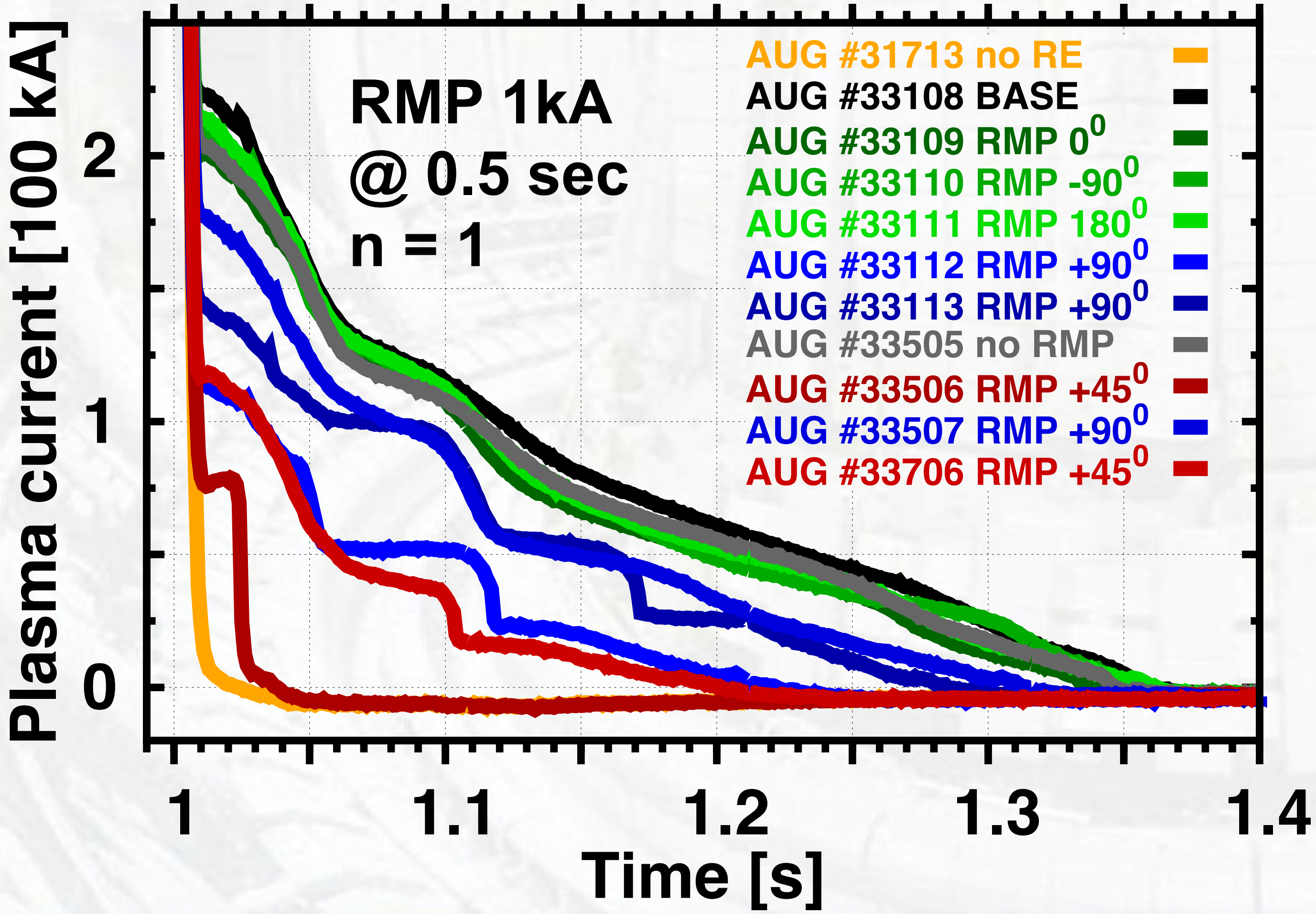
➡ Exponential decay fitted on the current evolution to extract a characteristic CQ time: $I_p \sim \exp\{-t/\tau_{CQ}\}$

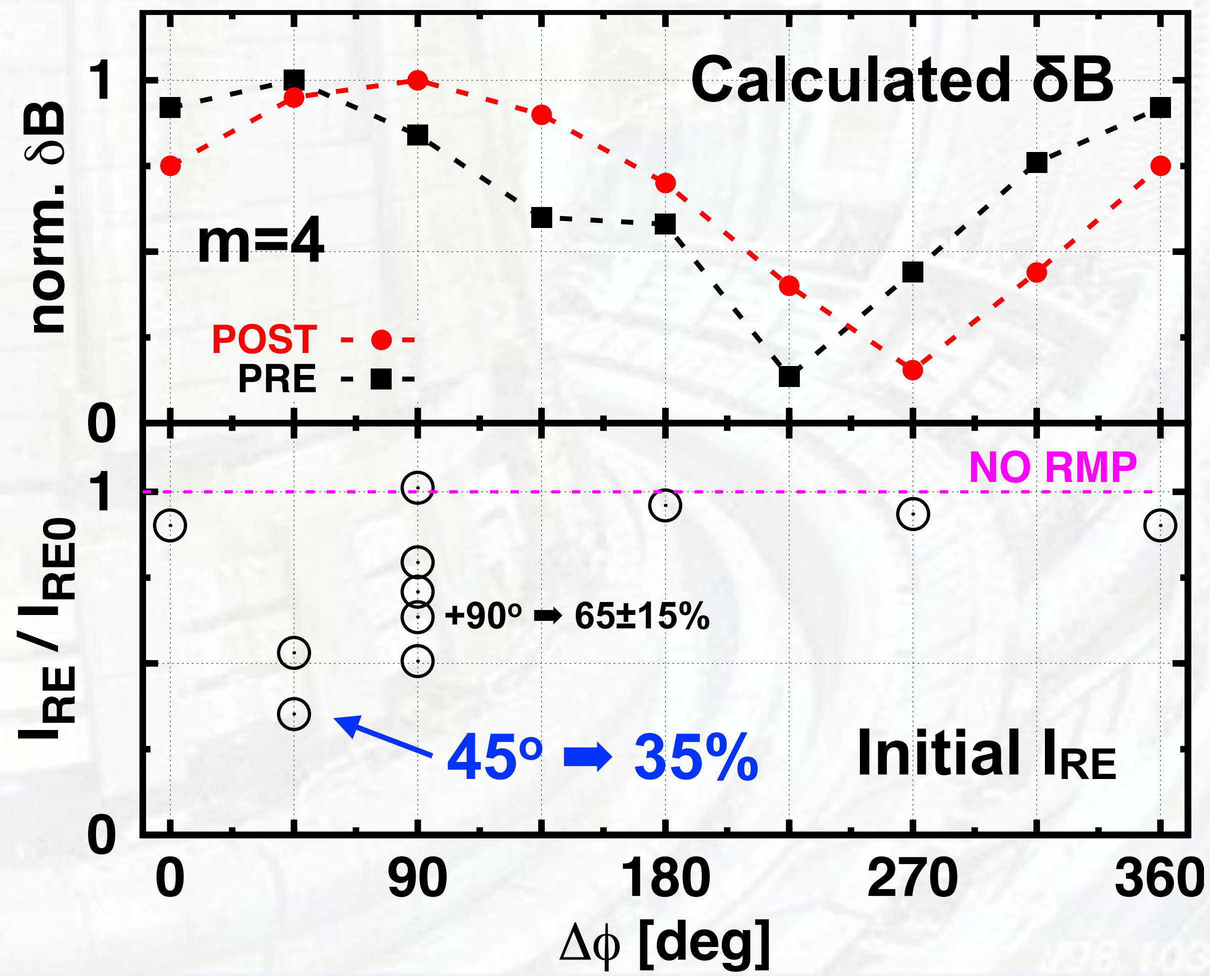


*GO: [Papp NF 2013]

The effect of RMPs

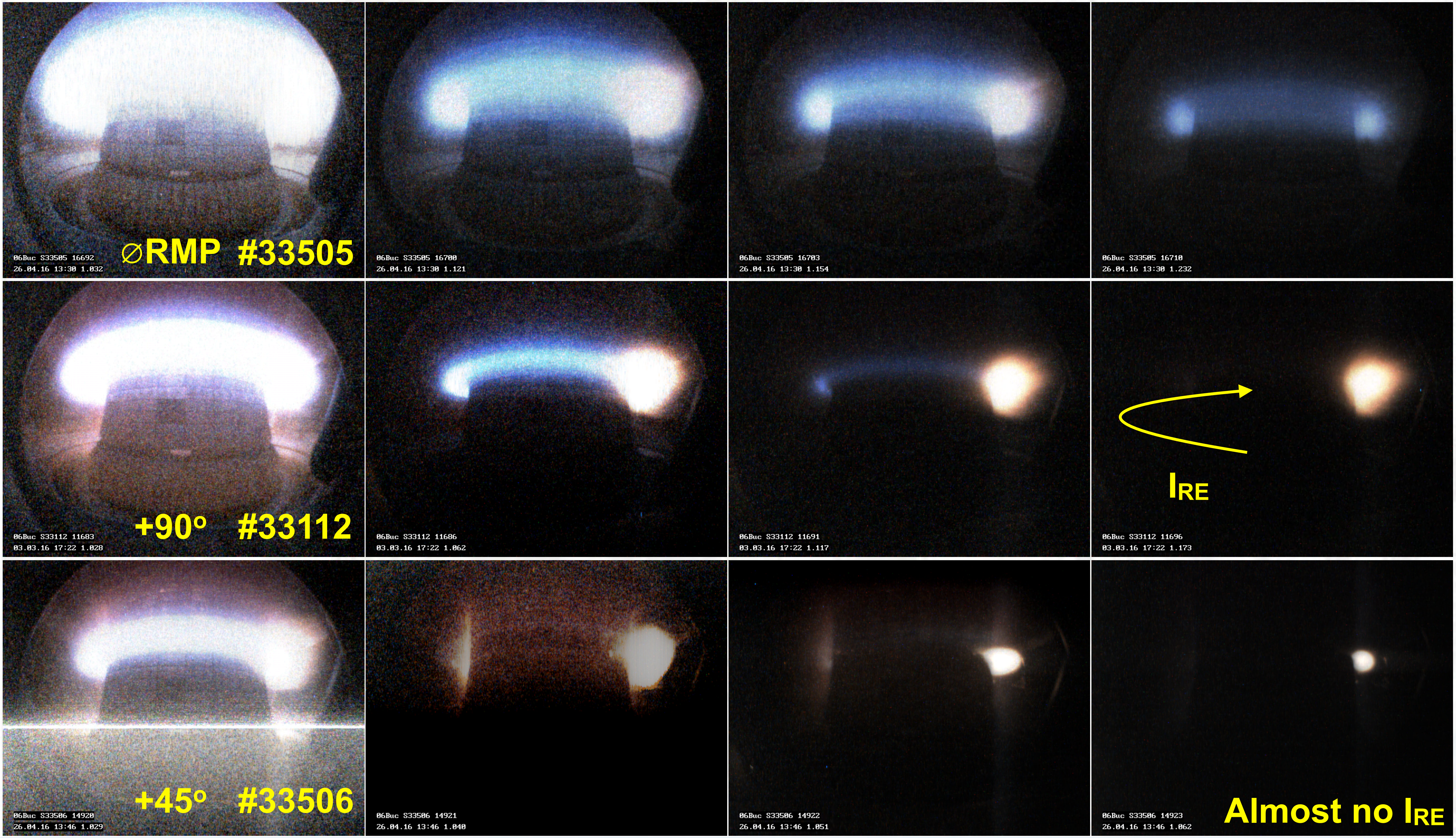
- **n=1 (1kA, @0.5s) RMP relative phase scan with the RE baseline**
- -90º, 0º and 180º doesn't make a difference in I_{RE}
- +90º has an effect, but there is a large scatter
- **+45º lead to the strongest effect so far, in agreement with theory**
  - ➡ RMP influences the disruption dynamics, not so much orbit losses
  - ➡ Direct or indirect influence (or both)? Great for MHD validation!
- Further analysis & modeling is ongoing [**M. Gobbin** *et al*]



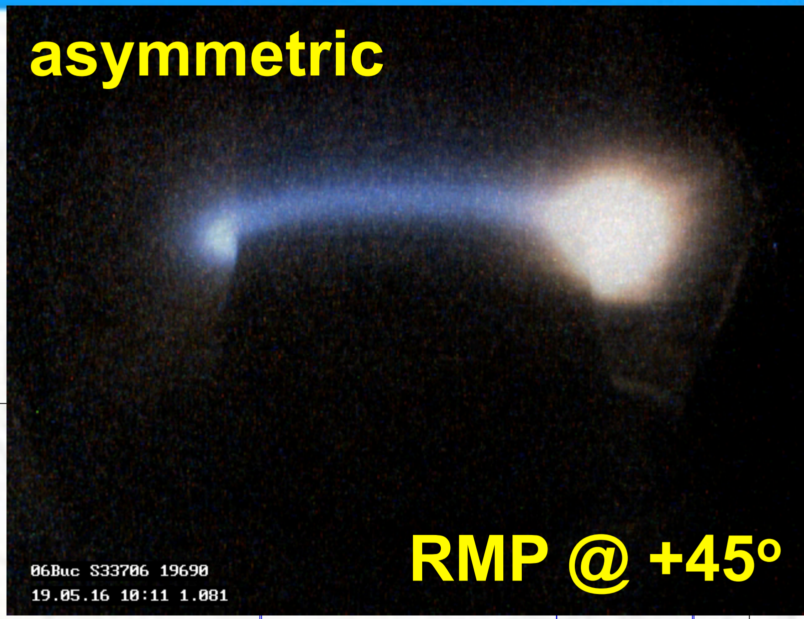


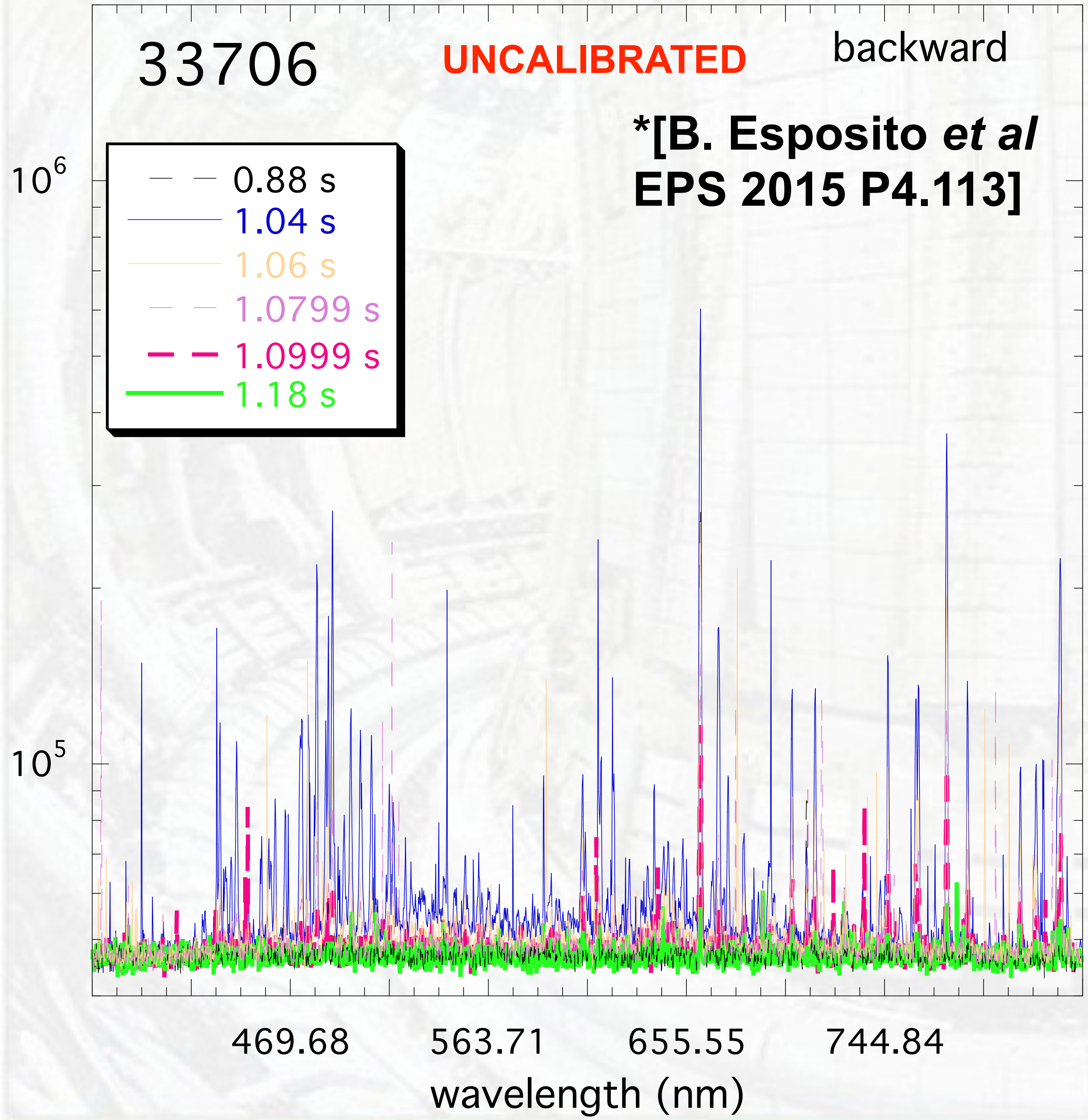
RMP is good for synchrotron imaging

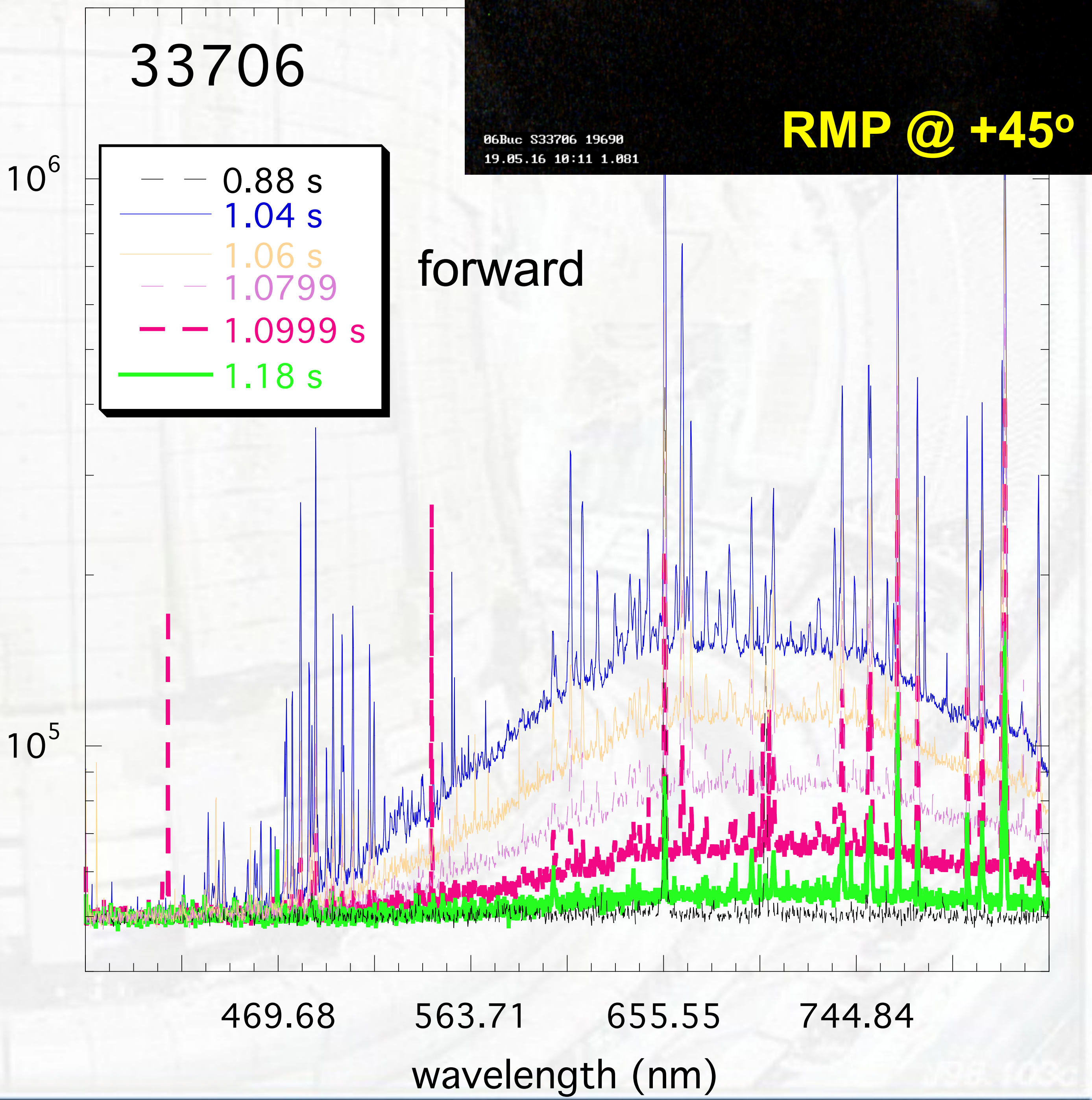
- CW asymmetry in radiation ➡ **conversion of E_{mag} to E_{kin}?**
  OR: higher pitch-angle scattering ➡ higher p_{perp}?



- **B. Esposito *et al.*, ENEA Frascati**
- MST 2 diagnostic development*, f. camera + {2x VIS + NIR} spectrometer

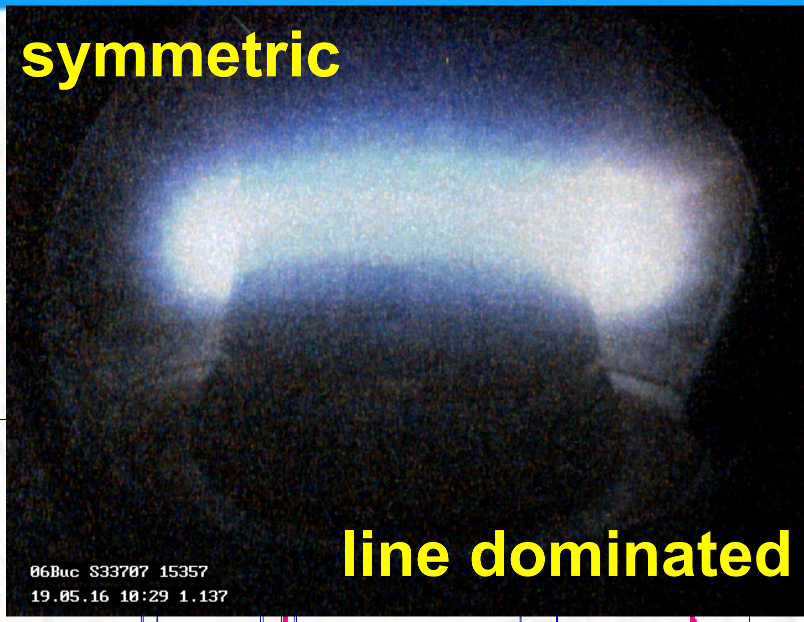


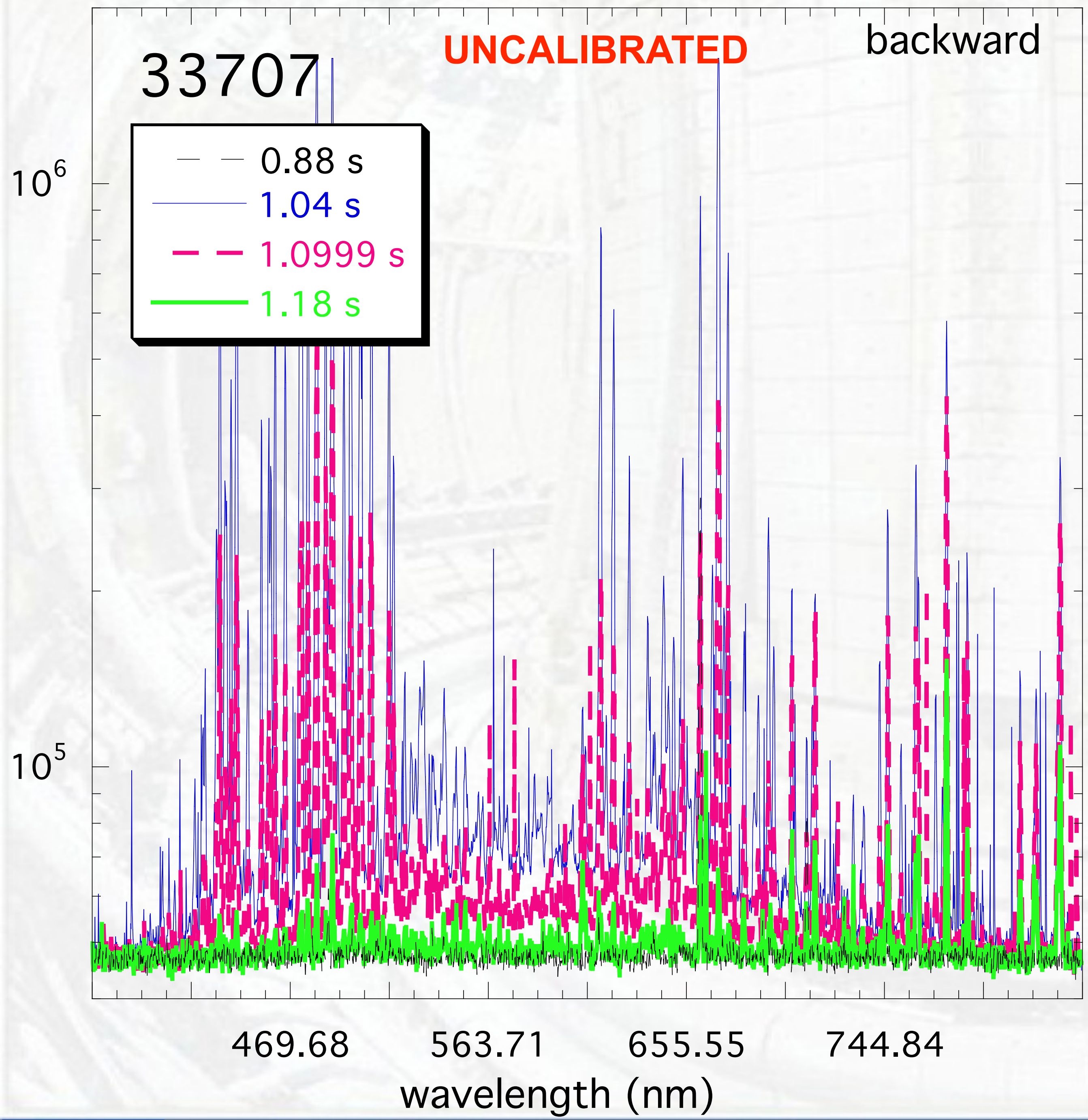


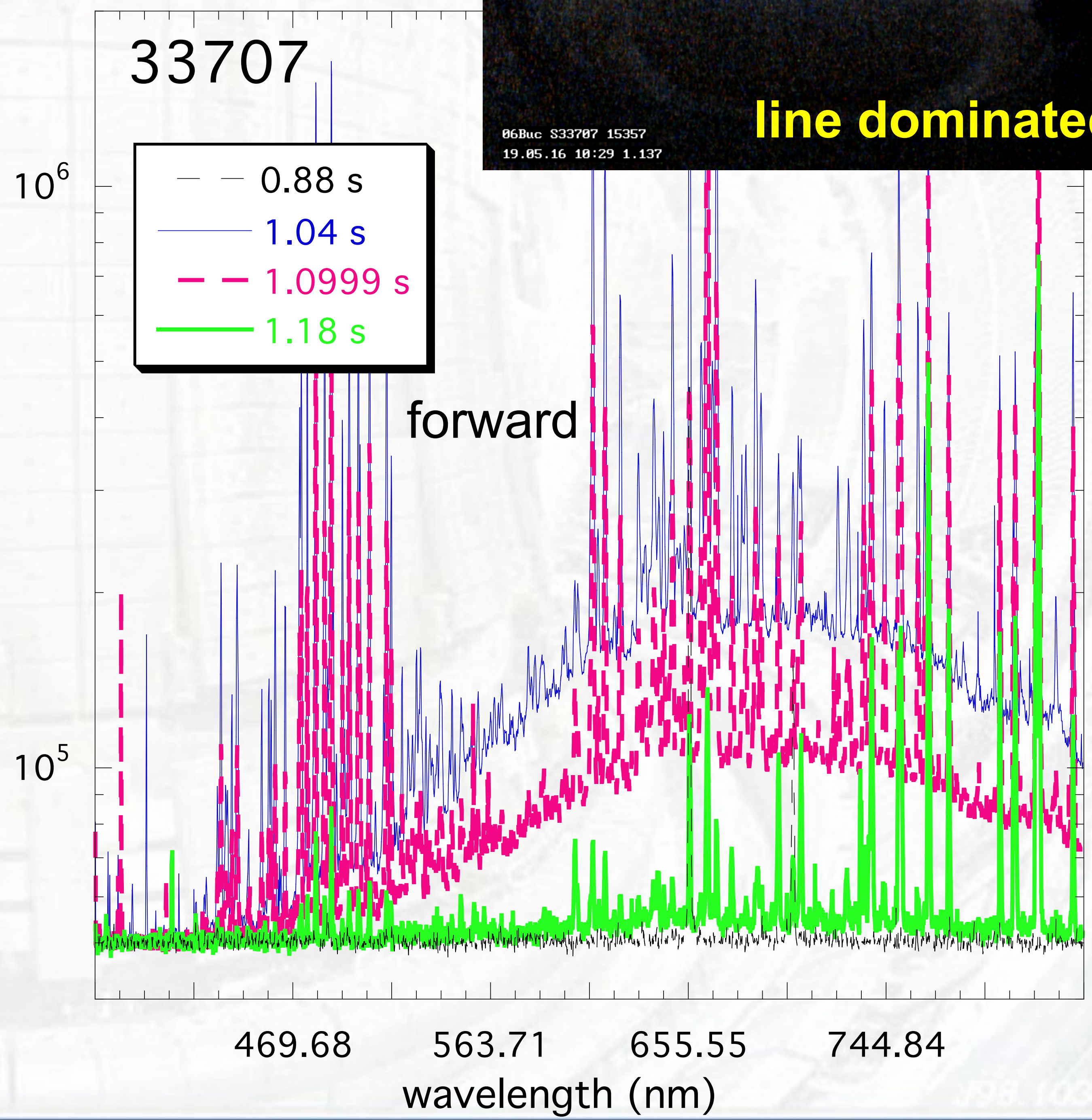


REIS - Runaway Electron Imaging & Spectrometer

- Spectrum highlights synchrotron contribution even if not visible to the naked eye ➡ convincing proof of principle

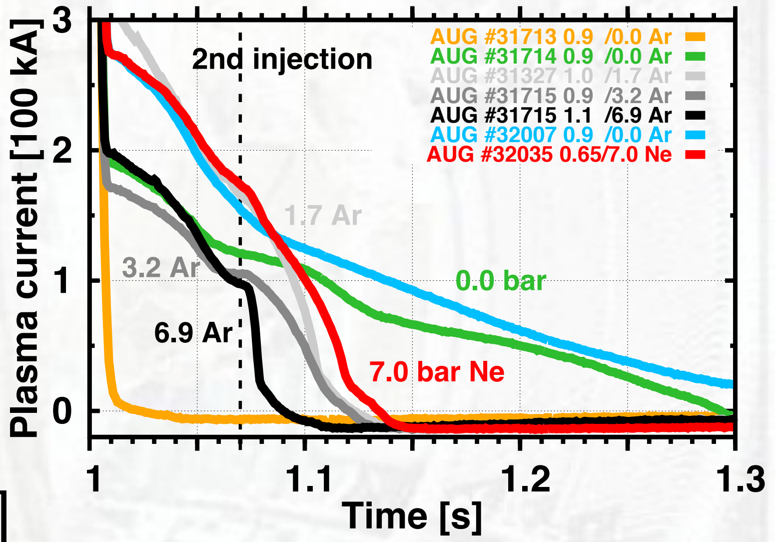


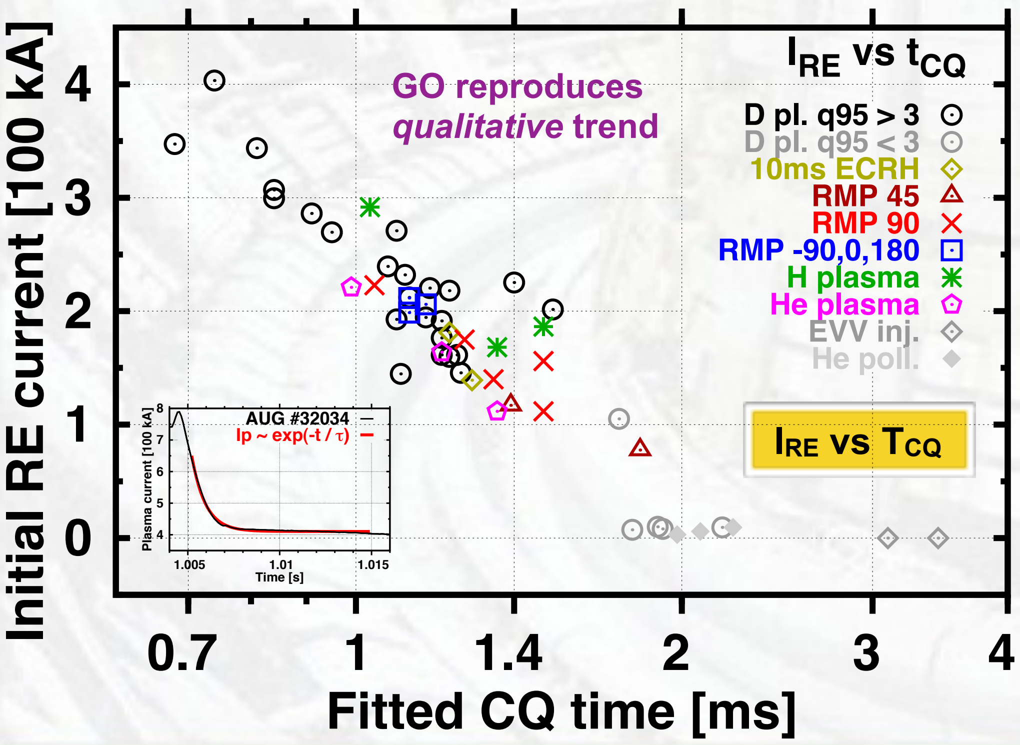


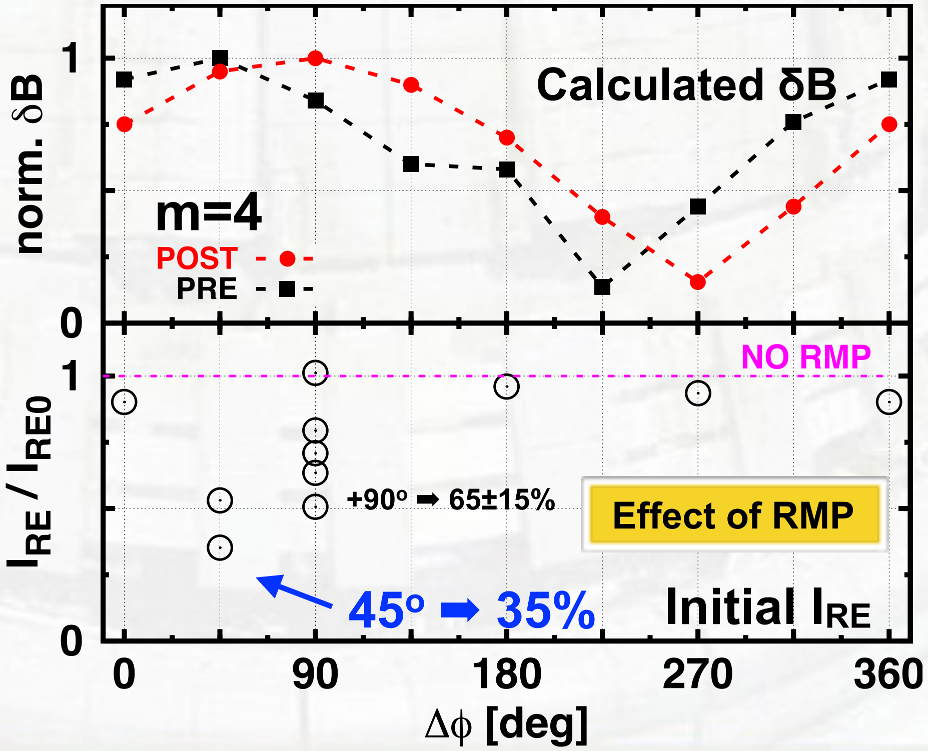


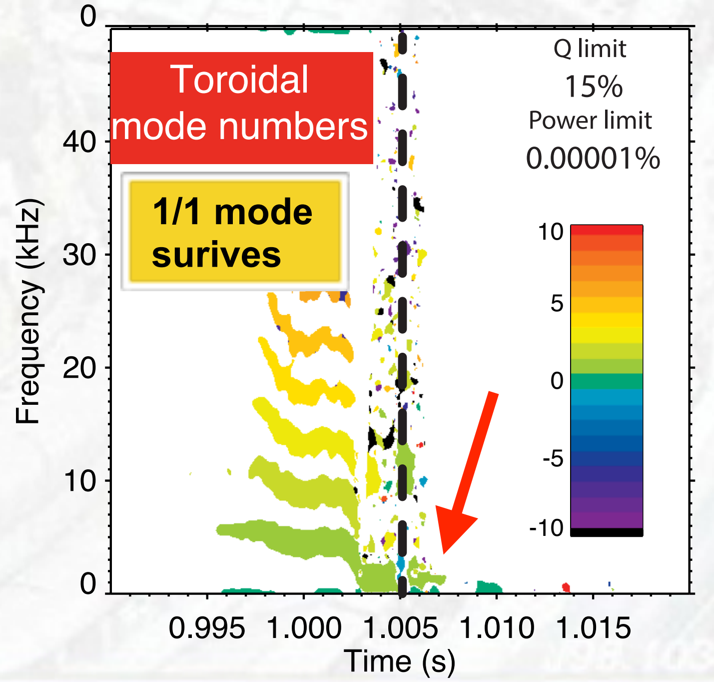
Summary: ASDEX Upgrade runaways

- **IPP/AUG is participating in runaway research**
  - ➡ We have a robust scenario for RE generation
  - ➡ Part of the core seems to survive the quench
- **Secondary injections can dissipate REs on AUG using any valve with Ar or Ne (more experiments are planned on this)**
- **RMPs can influence t_{CQ} ➡ I_{RE}**
- **Data analysis needs more work**
  - ➡ Assimilation rates from spectroscopy

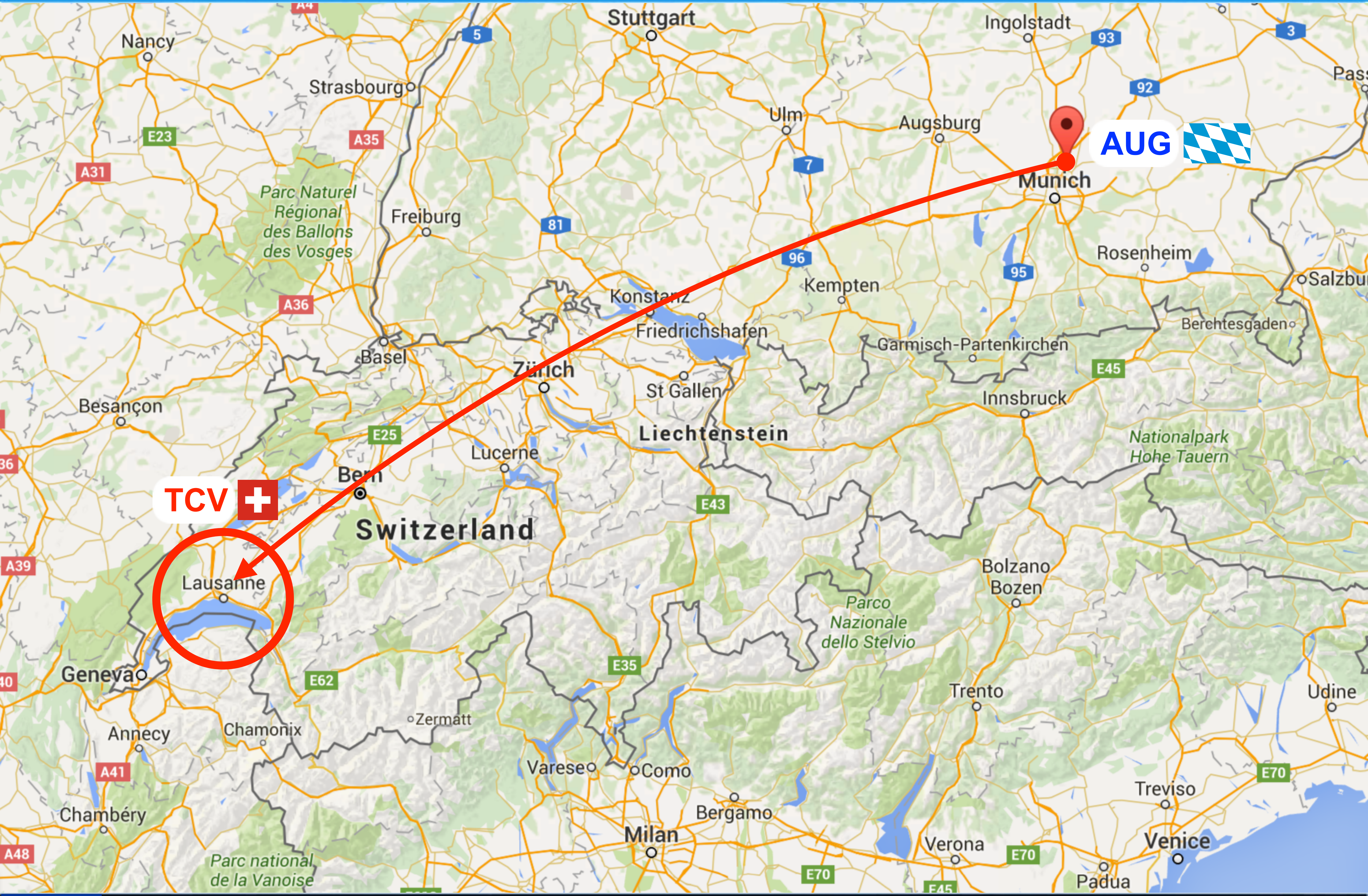








AUG ➡ TCV


AUG
TCV
Munich
Lausanne
Stuttgart
Ingolstadt
Nancy
Strasbourg
Ulm
Augsburg
Parc Naturel Régional des Ballons des Vosges
Freiburg
Rosenheim
Kempten
Salzbu
Konstanz
Friedrichshafen
Basel
Garmisch-Partenkirchen
Berchtesgaden
Zürich
St Gallen
Innsbruck
Besançon
Liechtenstein
Nationalpark Hohe Tauern
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Geneva
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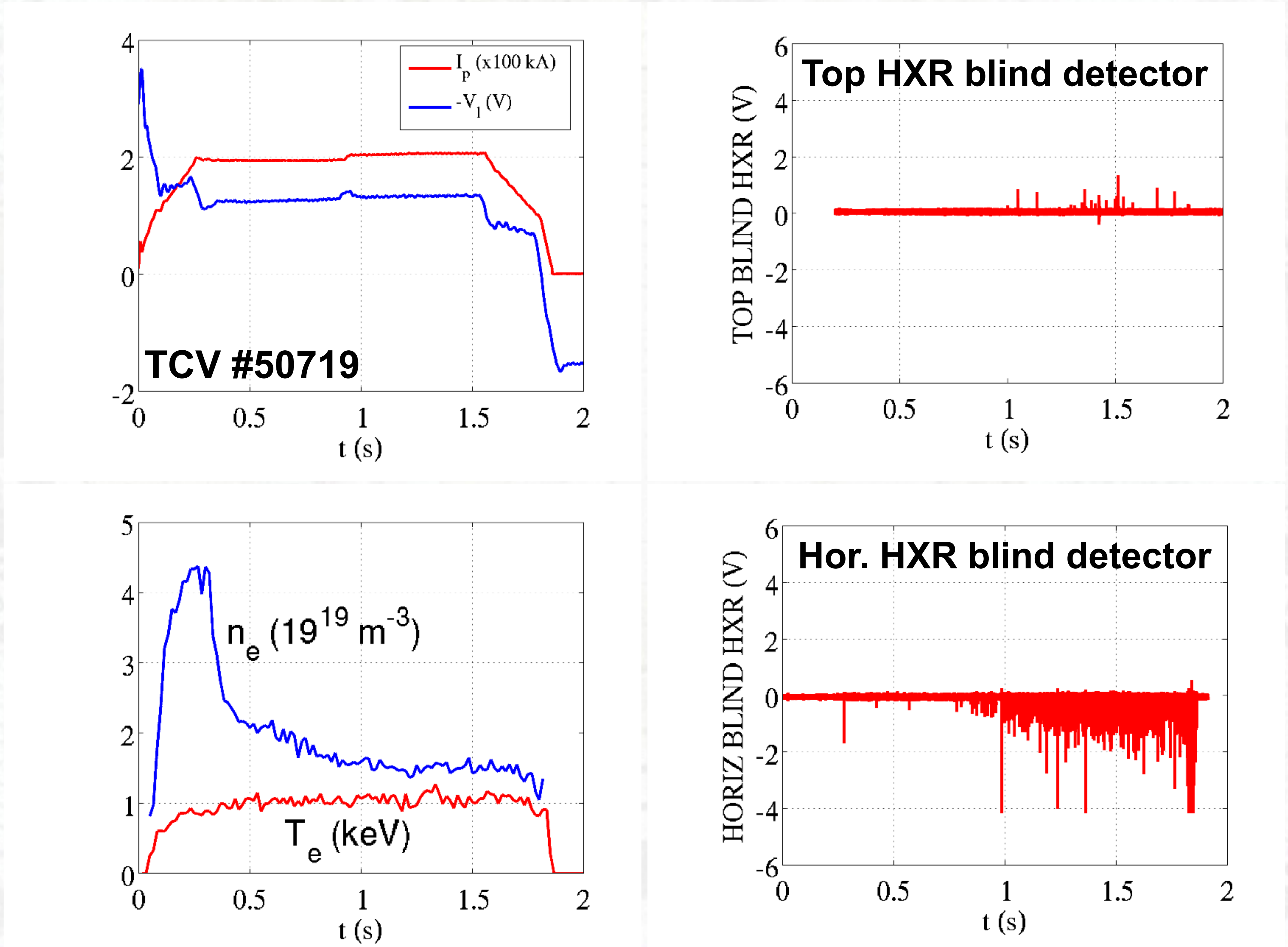
Annecy
Chamonix
Varese
Como
Treviso
Chambéry
Bergamo
Milan
Verona
Venice
Padua
Parc national de la Vanoise

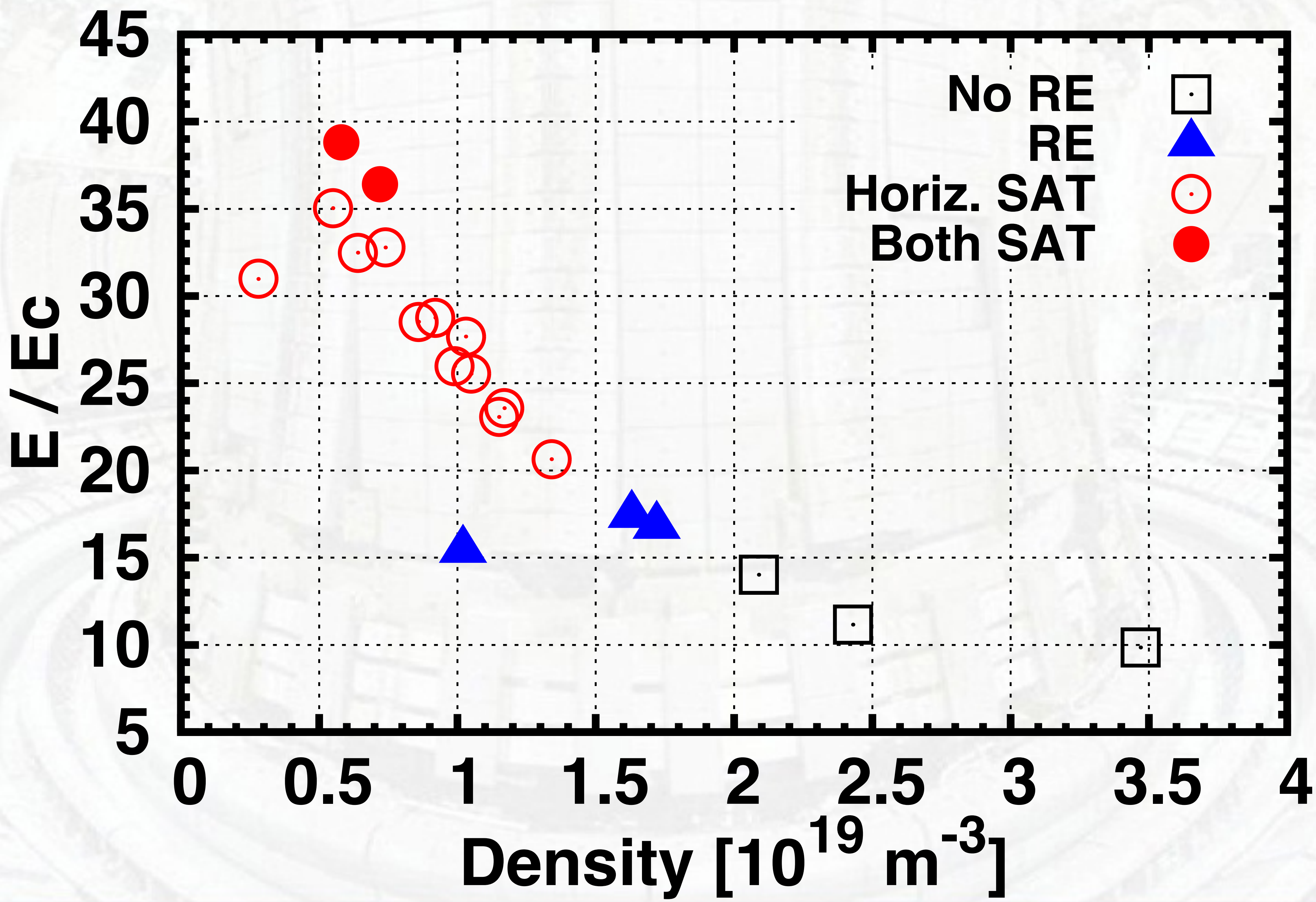
The TCV runaway scenarios

- Flat-top RE scenarios ➡ e.g. via density drop (DIII-D)



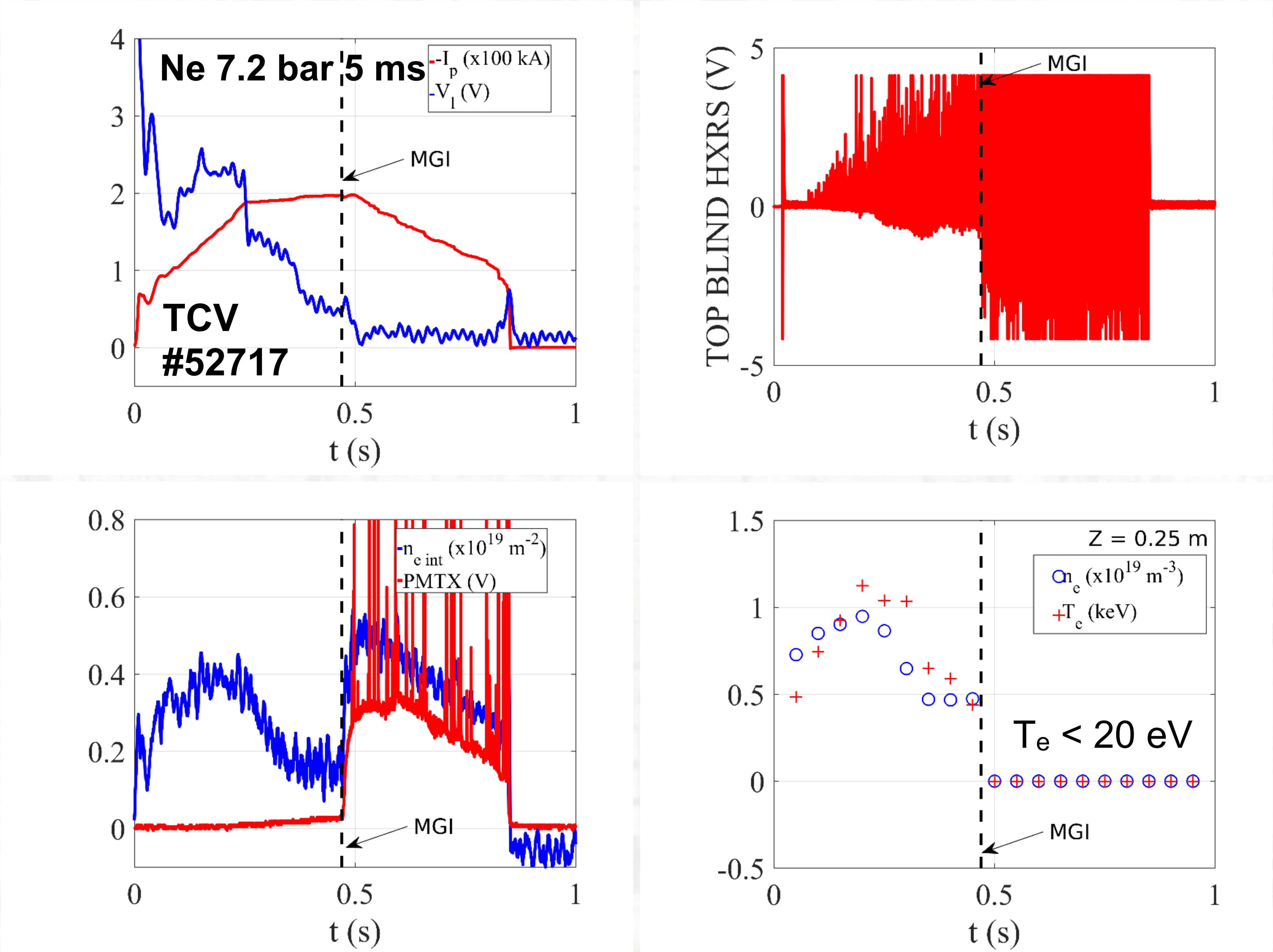
Flat-top RE - E_{crit} analysis

- 12 shots with n_{e0} from 0.3 to 3.5 x 10^{19} m^{-3}
- **No RE signal on HXR detectors for E/Ec < 15**
  - ➡ Note: numbers might change, but trend is clear



Post-disruption RE scenario

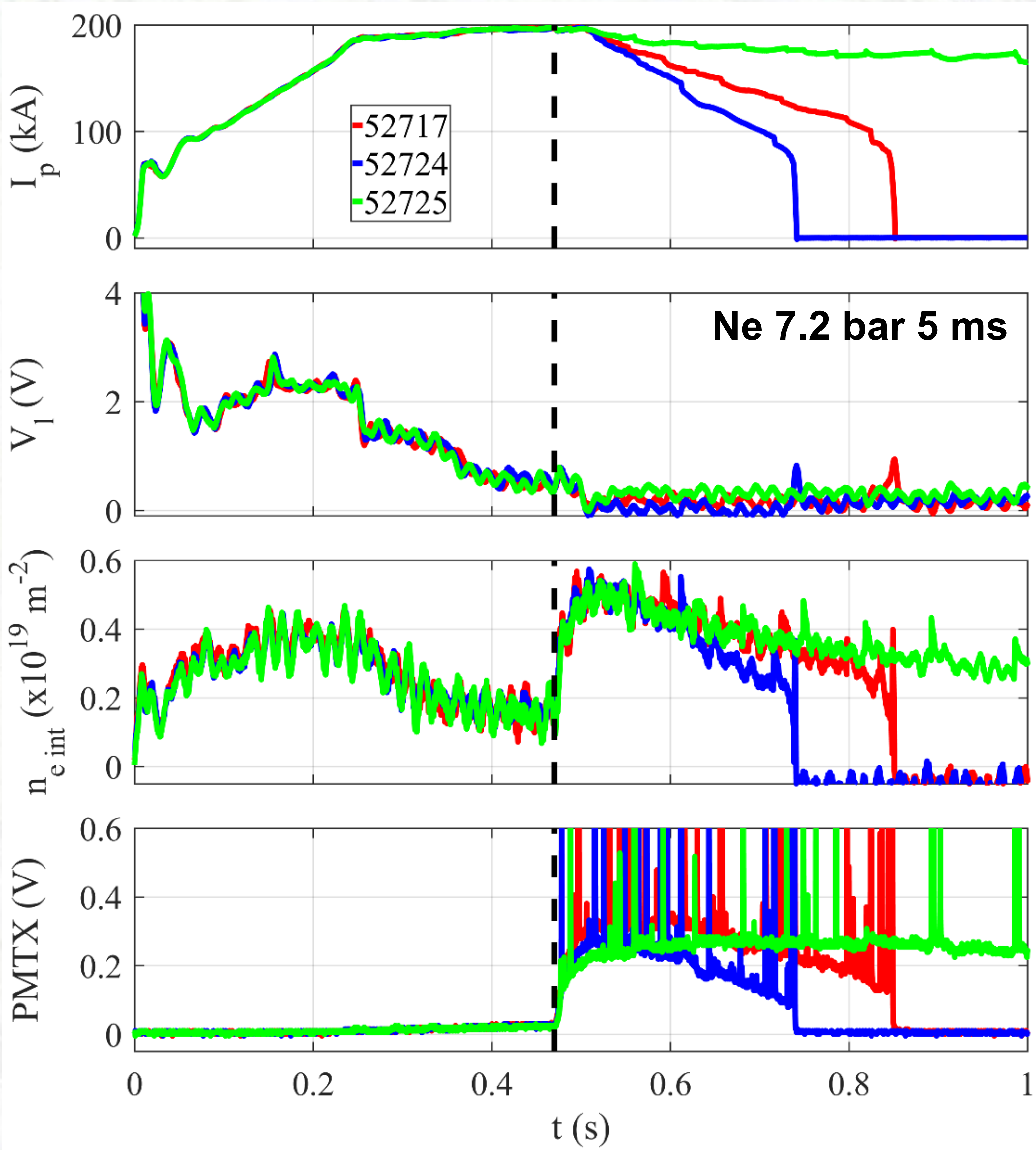
- Full OH ➡ RE conversion



I_{OH} control

- 52717 : $dI_{OH}/dt = 0$
- 52724 : $dI_{OH}/dt < 0$
- 52725 : $dI_{OH}/dt > 0$

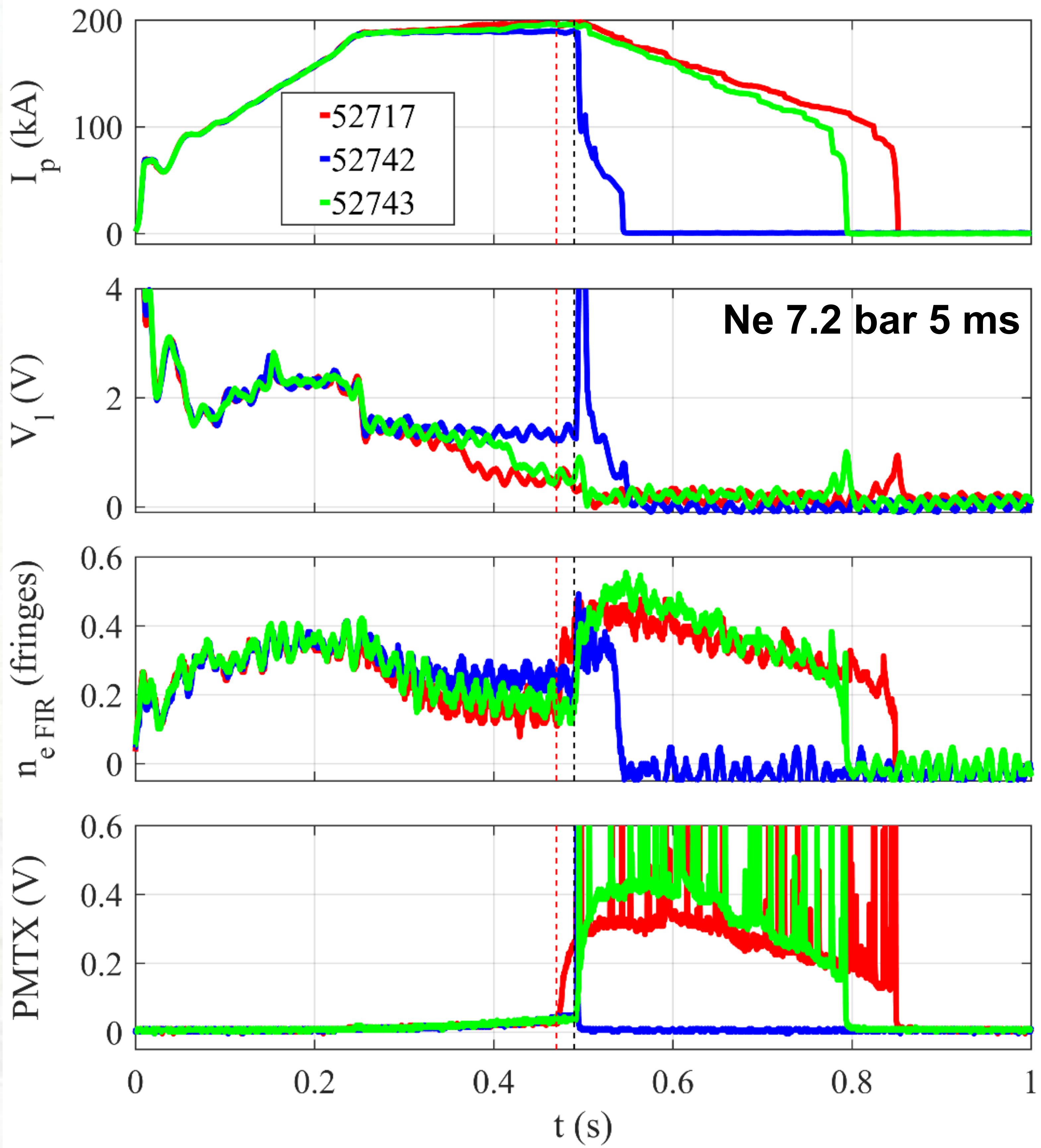
- **Reliable RE beam scenario**
- RE plateau current control



Effect of pre-MGI density

- 52717: $n_e = 1.5 \times 10^{18}\ m^{-2}$
- 52743: $n_e = 2.0 \times 10^{18}\ m^{-2}$
- 52742: $n_e = 2.5 \times 10^{18}\ m^{-2}$

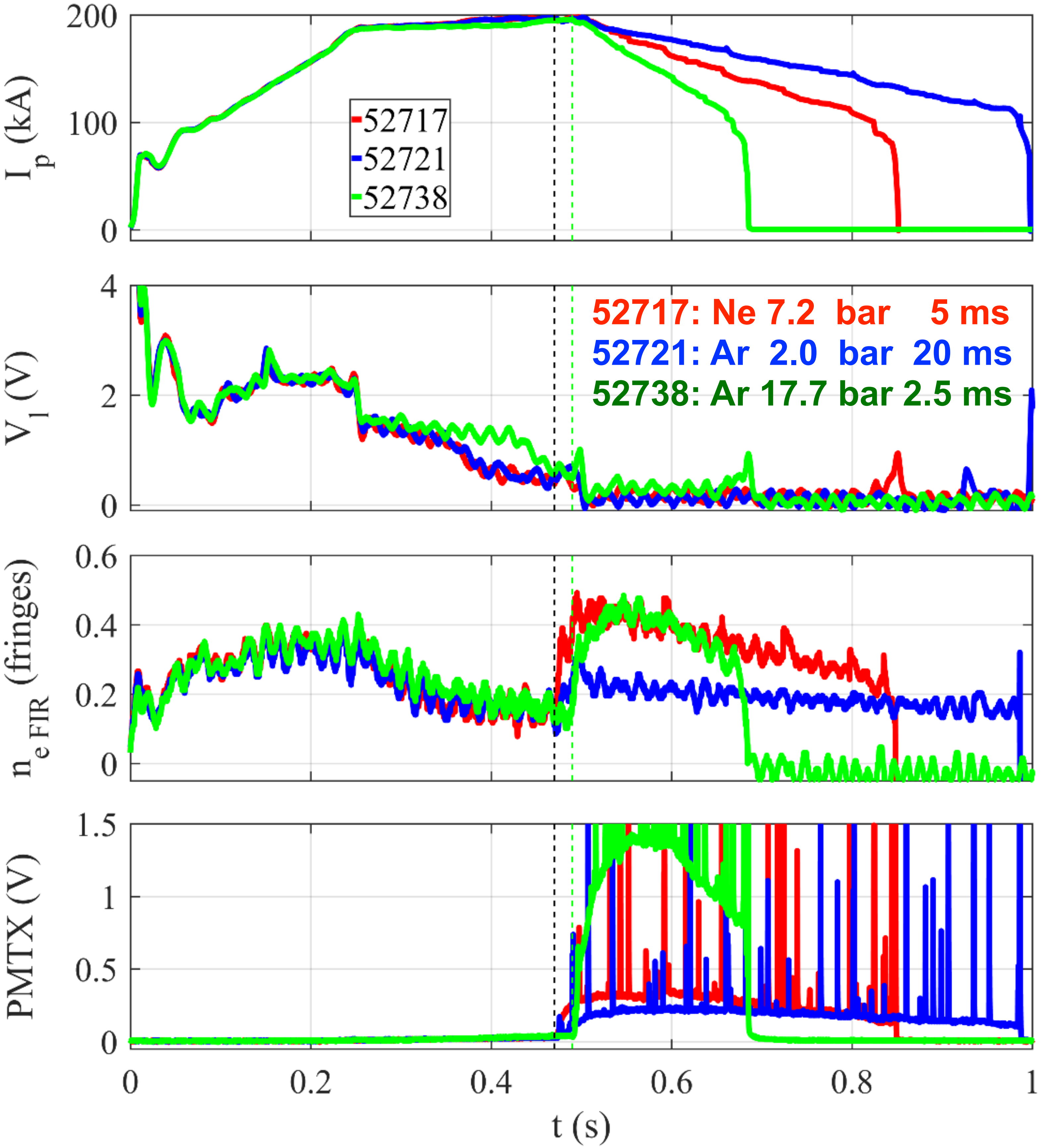
- **Importance of pre-MGI RE fraction**
- Finer scan is underway



MGI: effect of gas type

- 52717: Ne 7.2 bar 5 ms
- 52721: Ar 2.0 bar 20 ms
- 52738: Ar 17.7 bar 2.5 ms

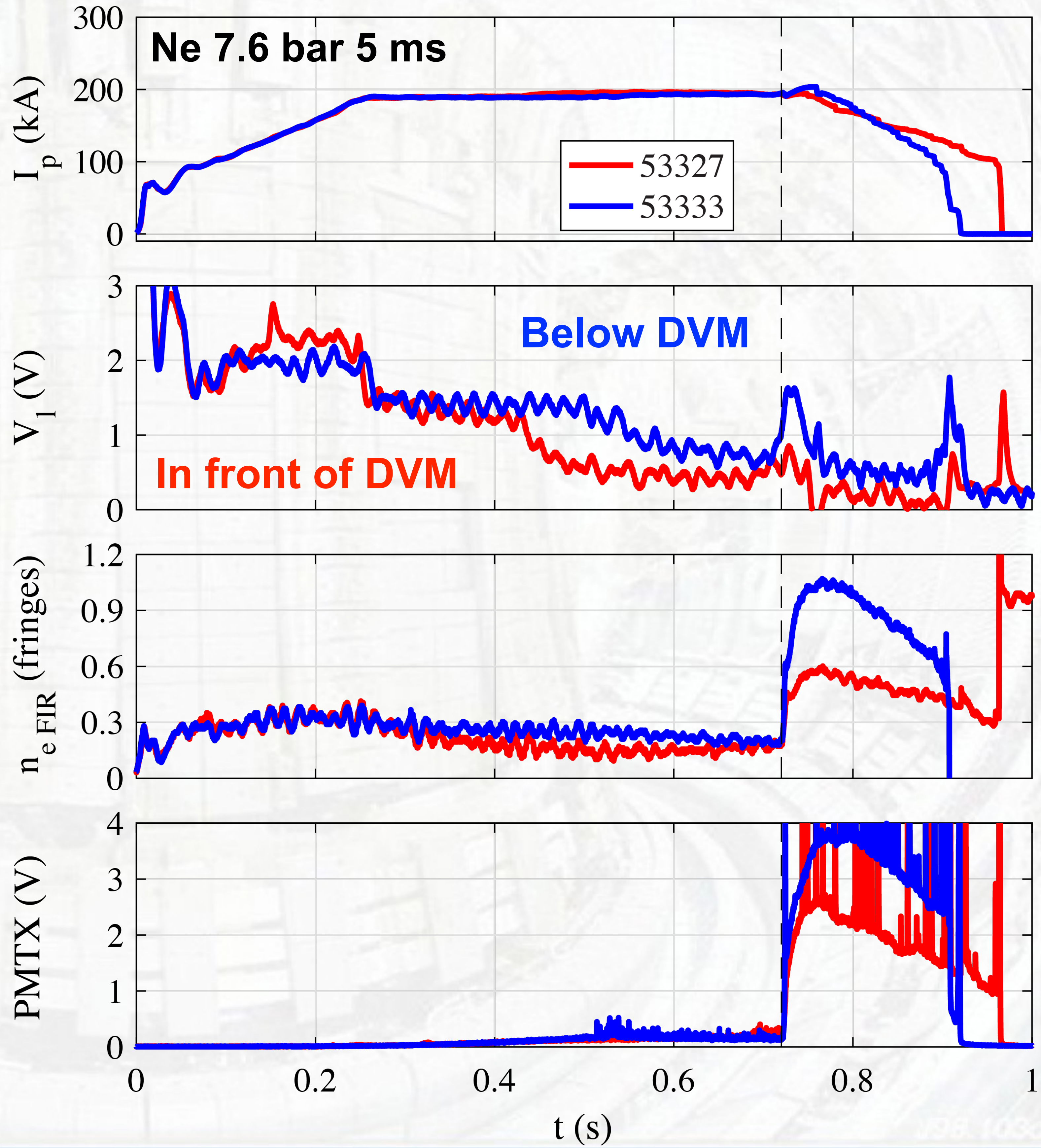
- **"Continuous flow" DMV**
- Injected gas amount to be calculated from DMV calibration



MGI: effect of Z position

- 53327: Z = 0.32 m
  (in front of DMV)
- 53333: Z = 0.16 m
  (bit below of DMV)

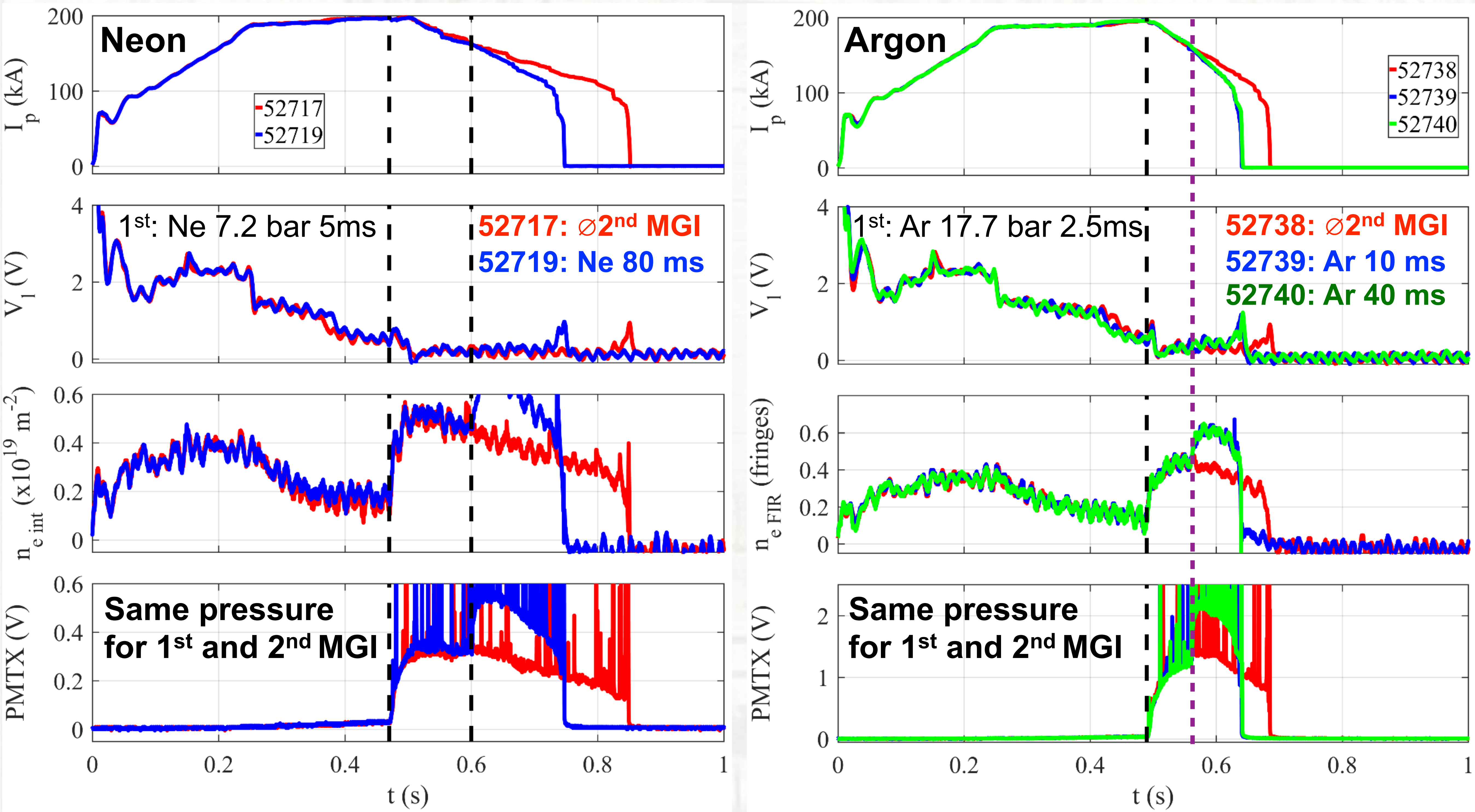
- Even better penetration when plasma is not directly in front of DMV?
- Needs more shots to confirm
  (couldn't finish last week)



Second MGI with Ne & Ar

- Density & HXR increase, faster RE ramp-down

➡ N_Z scaling is not trivial and not obvious (saturation?)



TCV runaway summary

- **Reliable RE generation scenarios**
- Flat-top: no RE HXR for E/Ec < 15
- **MGI: in very-low density plasma**
  - Full conversion of I_{OH} to I_{RE}
  - I_{OH} control during RE beam phase
  - ➡ Requires a significant pre-MGI RE
- **2nd MGI increases HXR and -dI/dt**
  - Works with both Ne and Ar
- **Experiments are not yet finished!**
  - ➡ Shaping studies
  - ➡ Beam position control